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PERFORMANCE CALCULATIONS OF ROCKET TRIPROPELLANT SYSTEMS

Thesis by

Lieutenant Commander Walter P. Murphy, Jr., U.S. Navy

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PERFORMANCE CALCULATIONS
OF
ROCKET TRIPROPELLANT SYSTEMS

Thesis by

LIEUTENANT COMMANDER WALTER P. MURPHY, JR., U. S. NAVY

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Annapolis, Md.

In Partial Fulfillment of the Requirements
For the Degree of
Aeronautical Engineer

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ABSTRACT

The purpose of this investigation is to determine the effect on the temperatures and the performance parameters of the addition of (1), liquid hydrogen, and (2), liquid ammonia to three bipropellant systems currently of interest. These bipropellant systems are: nitrogen tetroxide-hydrazine, hydrogen peroxide-hydrazine, and RFNA-hydrazine.

For each of the six tripropellant systems investigated the chamber temperature, exhaust temperature, and all the important parameters were calculated. These calculations for each system were carried out for both equilibrium flow and constant composition flow assumptions. All the results are listed in tables and the more important parameters are presented in graphical form as well.

One hydrogen containing system and one ammonia containing system are discussed in detail. General results for all systems include the fact that the largest proportionate decreases are observed in the variation of the exhaust and chamber temperatures whereas the specific impulse shows slight increases or proportionate decreases of much smaller magnitude than the proportionate decreases in temperatures.

Several new parameters are introduced in an effort to make possible the prediction of performances of a tripropellant system if the chamber temperature variation is known. These parameters may also be used in an indirect manner to illustrate the relative merit of liquid hydrogen and liquid ammonia as coolants in tripropellant systems.

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INTRODUCTION

One of the ever present problems in the design of any heat engine is the problem of removing the heat generated by the combustion at a rate high enough to prevent failure of the engine. In a thermal jet or rocket motor the temperatures of combustion and rates of heat transfer are greater than in any other practical heat engine. It is therefore easy to understand why this problem is one of the major problems in thermal jet and rocket motor design.

One solution to the problem is regenerative cooling. A regenerative cooling system maintains the motor wall material below its critical temperature by the circulation of the fuel or oxidant outside the motor wall. For many of the high performing propellant systems this method is inadequate and more effective cooling methods must be used (Cf. Ref. 1). Furthermore, many of the newer fuels and oxidants are not stable enough to permit their use in regenerative cooling systems.

Theoretically at all operating temperatures, and practically, at lower temperatures, it has been shown that film or transpiration cooling systems have certain advantages (Cf. Ref. 2). Also it appears that theoretically such cooling techniques are applicable to very hot propellant systems over longer periods of time.

In film or transpiration cooling, the coolant moves against the flow of heat through the wall material. On the hot side of the wall the coolant either evaporates, or takes part in the chamber reaction, or some combination of both. The extent of the mixing with the combustion gases is not yet known nor is it known what efficiency of absorption of radiant energy by a gas or vapor stream may be expected.

If adequate mixing and complete chemical reaction are assumed, the addition as a film or transpiration coolant of a properly chosen third component may have certain desirable effects on the calculated performance and adiabatic flame temperature. Although the extent to which the assumptions are valid must be determined experimentally, the theoretical effects on performance and gas temperature are of immediate interest since they will indicate the direction and order of magnitude of the effects that can be expected (Cf. Ref. 3).

Although liquid water has been seriously considered (Cf. Refs. 7 and 8), it has been previously shown that the most effective third components are liquid or gaseous hydrogen and liquid or gaseous ammonia (Cf. Refs. 3, 4, 6 and 7). These coolants or their dissociation products lower the chamber temperature by decreasing the available energy per pound of total propellant. The performance may increase because of the lower average molecular weight of the products of reaction. If, however, the performance decreases its proportionate decrease is always much less than the proportionate decrease in chamber temperature.

For these reasons the investigation of six tripropellant systems currently of interest was undertaken and the results are presented herein. The systems investigated are: nitrogen tetroxide-hydrazine with liquid hydrogen added, nitrogen tetroxide-hydrazine with liquid ammonia added, hydrogen peroxide-hydrazine with liquid hydrogen added, hydrogen peroxide-hydrazine with liquid ammonia added, RFNA-hydrazine with liquid hydrogen added, and RFNA-hydrazine with liquid ammonia added.

The performance parameters were evaluated for each tripropellant system at a mixture ratio corresponding to stoichiometric proportions with respect to the bipropellant oxidant and fuel, but with varying amounts of liquid hydrogen or liquid ammonia added in excess. Stoichiometric proportions of the bipropellant components were chosen since the chamber temperature is very nearly the maximum value at this mixture ratio and the reduction in flame temperature resulting from an added component would be most marked.

EXPLANATION OF SYMBOLS

a	Number of moles of water vapor (H_2O) in the products of reaction
b	Number of moles of hydrogen (H_2) in the products of reaction
c	Number of moles of hydroxyl ions (OH) in the products of reaction
d	Number of moles of atomic hydrogen (H) in the products of reaction
e	Number of moles of oxygen (O_2) in the products of reaction
f	Number of moles of atomic oxygen (O) in the products of reaction
g	Number of moles of nitrous oxide (NO) in the products of reaction
h	Number of moles of nitrogen (N_2) in the products of reaction
H	Number of gram atoms of hydrogen in the reactants
N	Number of gram atoms of nitrogen in the reactants
O	Number of gram atoms of oxygen in the reactants
a_c	Velocity of sound corresponding to chamber conditions (ft sec^{-1})
c	Effective exhaust velocity (ft sec^{-1})

c^*	Characteristic velocity (ft sec^{-1})
C_F	Theoretical thrust coefficient of nozzle
$(C_p)_c$	Apparent molar isobaric heat capacity of products of reaction at equilibrium chamber temperature (cal mol^{-1} ^{o}K^{-1})
$(C_v)_c$	Apparent molar isochoric heat capacity of products of reaction at equilibrium chamber temperature (cal mol^{-1} ^{o}K^{-1})
$\overline{C}_p$	Average apparent molar isobaric heat capacity of products of reaction during their passage through nozzle (cal mol^{-1} ^{o}K^{-1})
$\overline{C}_v$	Average apparent molar isochoric heat capacity of products of reaction during their passage through nozzle (cal mol^{-1} ^{o}K^{-1})
$E_{(I_{sp})}$	Dimensionless parameter equal to $\frac{I_{sp}}{I_{sp}^{o}} - \frac{T_c}{T_c^{o}}$
$E_{(h)}$	Dimensionless parameter equal to $\frac{h}{h^{o}} - \frac{T_c}{T_c^{o}}$
f_t	Nozzle throat area (sq in)
F	Thrust of rocket motor (lb)
g	Acceleration of gravity (arbitrarily chosen equal to 32.2 ft sec^{-2})
h	Altitude index (mi)

$\Delta H_{300}^{T_c}$, $\Delta H_{T_e}^{T_c}$, etc.	Change in enthalpy of the products of reaction (k cal) between superscript temperature (°K) and subscript temperature (°K)
$\delta H_{T_1}^{T_2}$	Enthalpy change in a specified system from T_1 to T_2 with the system in chemical equilibrium (k cal)
I_{sp}	Specific impulse of propellant (sec)
J	Mechanical equivalent of heat (4.186 x 10^{10} ergs k cal^{-1})
K_1, K_2, etc.	Equilibrium constants for particular reactions expressed in terms of partial pressures of components
K_{n_1}, K_{n_2}, etc.	Equilibrium constants for particular reactions expressed in terms of number of moles of components
m	Total weight of reactants (gm)
$\dot{m}$	Weight rate of flow through nozzle (lb sec^{-1})
$\bar{M}$	Average molecular weight of the products of reaction during their passage through the nozzle
$\bar{M}_c$	Average molecular weight of the products of reaction at equilibrium chamber temperature
n_p	Number of moles of products of reaction

$\overline{n}_p$	Average number of moles of products of reaction present during their passage through the nozzle
n^{T_c}, n^{2000}, etc.	Number of moles at temperature (°K) indicated by superscript
Δn_1, Δn_2, etc.	Number of moles of products minus the number of moles of reactants indicated in balanced equilibrium equation for a particular reaction
P	Total pressure of the products of reaction (atm.)
P_e	Nozzle exhaust pressure (psia)
P_c	Chamber pressure (psia)
$Q_{av}^{T_c}$, Q_{av}^{2500}, etc.	Heat available from completion of reaction at temperature (°K) as indicated by superscript (k cal)
$\Delta Q_{av}{}_{T_e}^{T_c}$	Change in heat available between T_c and T_e (k cal)
Q_f (reactants)	Heat of formation of the reactants at 300° K (k cal)
Q_f (products)	Heat of formation of the products at 300° K (k cal)
RFNA	Red fuming nitric acid (in this investigation, nitric acid with 6.8% by weight N_2O_4)
R_u	Universal gas constant (1.986 cal $mol^{-1}\ {}^{o}K^{-1}$, 8.315 x 10^7 ergs $mol^{-1}\ {}^{o}K^{-1}$)

T	Absolute temperature (°K)
T_c	Equilibrium chamber temperature (°K)
T_e	Exhaust temperature (°K)
$\bar{\rho}$	Average density of rocket propellant (gm cm^{-3})
γ	Ratio of isobaric to isochoric heat capacity (C_p/C_v)
γ_c	Ratio of apparent isobaric to isochoric heat capacity of products of reaction at equilibrium chamber temperature
$\bar{\gamma}$	Ratio of average apparent isobaric to isochoric heat capacity of the products of reaction during their passage through the nozzle
Γ'	A function of γ defined by $\Gamma^1 = \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$
$\Gamma'_{(\gamma_c)}$	Γ^1 evaluated for $\gamma = \gamma_c$
T_c^0, I_{sp}^0, h^0, etc.	Superscript zero indicates value of parameter for bipropellant system at stoichiometric mixture ratio

PART I

DISCUSSION OF ASSUMPTIONS AND INTRODUCTION OF PARAMETERS

The results of this investigation can be better evaluated when they are considered from the point of view of the assumptions on which they are based. Hence, before the methods of calculating the results are discussed and illustrated, it is necessary to set down the assumptions made concerning the combustion and flow conditions which must prevail if the theory and equations used are to be completely valid.

The assumptions are listed below in the approximate order in which they are applied in Parts II and III. Many of the assumptions are discussed in greater detail in these succeeding sections.

1. First of all, it is assumed that the propellants react completely and there is sufficient time for establishment of equilibrium concentrations of the normally unexcited components (H_2, H_2O, OH, H, O_2, O, NO, N_2, N) at the adiabatic flame temperature determined by the mass and heat balance.
2. All minor components are considered in these calculations except atomic nitrogen (N). Neglecting this component introduces an error which is smaller than possible errors in the equilibrium constants which determine the composition.

3. The equipartition of energy among the electronic, vibrational, and rotational energy levels is instantaneous, both in the chamber and in the nozzle expansion processes for the constant composition and equilibrium flow conditions assumed.
4. The gas mixture composition, ΔH^T_{300}, and Q^T_{av} are assumed to be linear over temperature ranges of one hundred degrees Kelvin.
5. For calculation of the characteristic velocity, the ratio of specific heats (γ) is assumed to be the ratio of the specific heats at the equilibrium chamber temperature (γ_c). This was calculated on the basis of the enthalpy change over the one hundred degree temperature interval nearest the chamber temperature at constant pressure, the chamber pressure. For calculation of the exhaust temperature, a constant average ratio of specific heats $(\overline{\gamma})$ is used. This was calculated on the basis of the enthalpy change during the nozzle expansion process.
6. The function Γ', defined below, can be represented by a linear function of γ (Cf. Ref. 5). By definition,

$$\Gamma' = \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

By linear approximation,

$$\Gamma' = .1047 + .5048\gamma$$

This linear approximation was checked over the range of γ encountered in these calculations and found to be equal to the value calculated by the longer expression to within one-half per cent.

7. In the calculations in which equilibrium flow is assumed to be maintained in the nozzle expansion process, the gas mixture composition changes continuously and instantaneously in accordance with the temperature and pressure variations as determined by the corresponding chemical equilibrium constants.
8. In the calculations in which constant composition flow is assumed to be maintained, the gas mixture remains constant as the gases flow from combustion chamber to the exhaust atmosphere. The composition, therefore, is equal to that at the adiabatic flame temperature (T_c) in the chamber.
9. The chamber pressure (P_c) is taken to be 300 psia for all calculations presented here and the nozzle exhaust pressure (P_e) is assumed to be 14.7 psia.
10. Steady flow conditions prevail throughout the nozzle. It is assumed that shock disturbances may be neglected and that the velocity profile is flat. It is further assumed that one dimensional flow equations are valid.
11. Since the expansion process is taken to be isentropic, entropy changes from viscous and friction effects are assumed to be negligible.
12. The enthalpy of the reaction products is independent of the pressure. This is essentially

true since the highest pressures used in the calculations are relatively low.

10. The velocity of the reaction products in the chamber is negligible when compared with their velocity in the exhaust.

The performance parameters calculated in this investigation are those currently in use at the Jet Propulsion Laboratory, California Institute of Technology, to aid in judging the relative merit of a liquid rocket propellant system. Their definitions, therefore, are reviewed here only briefly.

The characteristic velocity (c*) is defined arbitrarily to relate mass flow, chamber pressure and nozzle throat area. As such, it is a measure of the efficiency of the combustion process and can be experimentally determined from easily measured quantities. A theoretical value can be calculated from T_c, γ_c, and $\overline{M}_c$ for a given propellant system and combustion conditions. The theoretical value is a measure of the merit of the propellant and is usually about ten percent greater than the experimentally determined value. Comparison of the characteristic velocity obtained in practice and, in theory, is an aid in combustion chamber design.

The effective exhaust velocity (c) is that velocity which when multiplied by the mass rate of flow will give the thrust. The effective exhaust velocity is the nozzle exit velocity when conditions are as assumed in this thesis. Here again is a parameter which can be computed theoretically and also can be determined experimentally from easily measured quantities.

Closely related to the effective exhaust velocity is the specific impulse (I_{sp}). This is defined as the pounds of thrust per pound of propellant consumed per second. It is obtained by dividing the effective exhaust velocity by the acceleration of gravity.

It has been found useful in practice to define a nozzle thrust coefficient (C_F) which is a function of the chamber pressure, nozzle throat area, and the thrust. Thus, the thrust coefficient can be determined experimentally and compared with the theoretical value. The theoretical value is obtained by dividing the effective exhaust velocity by the characteristic velocity.

The altitude index of a propellant system is the vertical range which a large rocket of an arbitrarily chosen total impulse would attain for a particular set of given assumptions. Once the total impulse has been chosen and the assumptions made, the altitude index is a function of the specific impulse and the mean propellant density. Therefore, the altitude index gives the relative value of a propellant system if used in a definite rocket which further satisfies the given conditions of manufacture and operation. These conditions assume the use of a bipropellant system, but the application to the systems studied here is still of value. The values of altitude index computed are only slightly higher than they should be.

PART II

DEVELOPMENT OF THE EQUATIONS FOR SOLVING THE COMPOSITION OF THE PRODUCTS OF REACTION INCLUDING A SAMPLE CALCULATION

The method of solving the composition of the products of reaction presented here is quite similar to that used at the Jet Propulsion Laboratory. However, it was arrived at independently and it was used for all composition solutions necessary in the preparation of the results contained in this thesis.

The propellant systems investigated contained only three chemical elements: hydrogen, nitrogen, and oxygen. The following symbols are employed to represent the atomic and molecular species present in the combustion gases:

a = number of moles of water vapor (H_2O)

b = number of moles of hydrogen (H_2)

c = number of moles of hydroxyl ion (OH)

d = number of moles of atomic hydrogen (H)

e = number of moles of oxygen (O_2)

f = number of moles of atomic oxygen (O)

g = number of moles of nitrous oxide (NO)

h = number of moles of nitrogen (N_2)

H = number of gram atoms of hydrogen

O = number of gram atoms of oxygen

N = number of gram atoms of nitrogen

Thus, the general chemical equation for any system involving only hydrogen, nitrogen, and oxygen becomes:

$H + N + O = aH_2O + bH_2 + cOH + dH + eO_2 + fO + gNO + hN_2$

It can be seen that the problem is to solve for the eight unknown quantities: a, b, c, d, e, f, g, and h.

From this general chemical equation, three equations involving atom balances can be written:

Sum of H atoms: $H = 2a + 2b + c + d$ (1)

Sum of O atoms: $O = a + c + 2e + f + g$ (2)

Sum of N atoms: $N = g + 2h$ (3)

The remaining five equations necessary for the solution of the problem are obtained by assuming that complete equilibrium is reached and employing this fact to obtain five more independent relationships among the eight unknowns. The equilibrium reactions involved and the corresponding equations in terms of the unknown quantities are as follows:

$\frac{1}{2}N_2 + H_2O = NO + H_2$ $(\Delta n_5 = 0.5)$

$$K_{n_5} = \frac{g\ b}{h^{.5}a} \qquad (4)$$

$2\ H_2O = O_2 + 2H_2$ $(\Delta n_6 = 1)$

$$K_{n_6} = \frac{e\ b^2}{a^2} \qquad (5)$$

$H_2O = O + H_2$ $(\Delta n_7 = 1)$

$$K_{n_7} = \frac{f\ b}{a} \qquad (6)$$

$\frac{1}{2}H_2 = H$ $(\Delta n_9 = 0.5)$

$$K_{n_9} = \frac{d}{b^{.5}} \qquad (7)$$

$H_2O = OH + \frac{1}{2}H_2$ $(\Delta n_{10} = 0.5)$

$$K_{n_{10}} = \frac{c\ b^{.5}}{a} \qquad (8)$$

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In these equations the equilibrium constants are expressed in terms of the number of moles of the components. In Table I the numerical values of the equilibrium constants are expressed in terms of partial pressures, K's. These were converted to K_n's by using the following general relationship,

$$K_n = K \left[\frac{n_p}{P}\right]^{\Delta n} \qquad (9)$$

where n_p = number of moles of products of reaction

P = total pressure of products of reaction (atm.)

Δn = number of moles of products less number of moles of reactants as determined from the balanced chemical equation for the particular equilibrium reaction

Since the K_n's depend on the total number of moles of products, we have in effect introduced a ninth unknown, n_p, where

$$n_p = a + b + c + d + e + f + g + h \qquad (10)$$

which must also be estimated for each particular solution.

Assuming a value for "n_p", these equations can now be used to resolve the composition of the chamber or exhaust gases. Rewriting (1),

$$2a + 2b + c + d = H$$

From (8), $$c = \frac{K_{n_{10}}\, a}{b^{.5}}$$

From (7), $$d = K_{n_9}\, b^{.5}$$

Substituting for "c" and "d" in (1),

$$2a + 2b + \frac{K_{n_{10}}\, a}{b^{.5}} + K_{n_9}\, b^{.5} = H$$

Solving above equation for "a",

$$a = \frac{H\,b^{.5} - K_{n_9}\,b - 2b^{1.5}}{2b^{.5} + K_{n_{10}}} \tag{11}$$

From (8), $$c = \frac{K_{n_{10}}\,a}{b^{.5}} \tag{12}$$

From (7), $$d = K_{n_9}\,b^{.5} \tag{13}$$

From (5), $$e = \frac{K_{n_6}\,a^2}{b^2} \tag{14}$$

From (6), $$f = \frac{K_{n_7}\,a}{b} \tag{15}$$

From (2), $$g = O - a - c - 2e - f \tag{16}$$

From (3), $$h = \tfrac{1}{2}\,(N - g) \tag{17}$$

Repeating (10), $$n_p = a + b + c + d + e + f + g + h \tag{18}$$

Repeating (4), $$K_{n_3} = \frac{g\,b}{h^{.5}a} \tag{19}$$

These nine equations, (11) through (19), and the general relationship, Equation (9), were used to solve the composition at one hundred degree intervals of temperature by using the following trial and error procedure.

1. Estimate "n_p" and evaluate the equilibrium constants (K_n's) for the corresponding chamber or exhaust pressure. Values of the equilibrium constants are listed in Table I.
2. Estimate "b", and using equations (11) through (17), solve for the other components.
3. From equation (18), find "n_p". Compare this with estimated value of Step 1.

4. From equation (19), find k_{n_3}. Compare this with the value of Step 1. The value of k_{n_3} of Step 1 is in error only if "n_p" estimate is incorrect.
5. Repeat the process using a new estimate of "n_p" and "b" until the computed "n_p" agrees with the estimated value, and k_{n_3} from equation (19) agrees with true value of step 1.
6. As a check on numerical work, equations (1), (2), and (3) should be used.

To illustrate this method a sample calculation will be presented here. The system chosen for the calculation is the tripropellant system consisting of a stoichiometric mixture of nitrogen tetroxide and hydrazine with one half mole of liquid hydrogen added. The equation for this reaction at 300° K is:

$$N_2O_4 + 2N_2H_4 + 0.5H_2(l) = 4H_2O(l) + 3N_2 + 0.5H_2 \quad (20)$$

At an elevated temperature:

$$N_2O_4 + 2N_2H_4 + 0.5H_2(l) = aH_2O(g) + bH_2 + cOH$$
$$+ dH + eO_2 + fO + gNO + hN_2$$

From the left hand side of (20), it can be seen that

$H = 9.000$ $\quad$ $N = 6.000$ $\quad$ $O = 4.000$

The problem is to solve the composition of the products of this reaction when it occurs in a rocket motor with chamber pressure of P_c = 300 psia at an estimated chamber temperature of T_c = 3200° K.

The results of the solution are presented in Table A. In the first attempt at solution, "n_p" was assumed to be

TABLE A

RESULTS OF SAMPLE CALCULATION
OF THE COMPOSITION OF THE PRODUCTS OF REACTION
For T = 3200° K, P = P_c = 20.41 atm.

SOLUTION		1	2	3
Step 1:	n_p (est.)	7.960	7.960	7.840
	K_{n_3}	0.00807	0.00807	0.00802
	K_{n_6}	0.00275	0.00275	0.00271
	K_{n_7}	0.00742	0.00742	0.00731
	K_{n_9}	0.1755	0.1755	0.1744
	$K_{n_{10}}$	0.0678	0.0678	0.0674
Step 2:	b (est.)	0.800	0.750	0.770
	a	3.489	3.555	3.519
	c	0.265	0.277	0.270
	d	0.157	0.152	0.153
	e	0.052	0.062	0.057
	f	0.032	0.035	0.033
	g	0.110	0.031	0.064
	h	2.945	2.965	2.968
Step 3:	n_p	7.850	7.826	7.834
Step 4:	K_{n_3}	0.0147	0.00380	0.00812

7.850 and "b", 0.800. This solution gave a K_{n_3} (Step 4) much greater than K_{n_3} (Step 1), indicating that the first estimate of "b" was too high. The n_p (Step 3) was less than n_p (Step 1).

The second attempt to obtain a correct solution was made with "b" = 0.750. A new estimate of "n_p" was not made due to the relatively large error of the first solution plus the fact that the solution is much more sensitive to changes in "b". This solution gave a K_{n_3} (Step 4) less than K_{n_3} (Step 1), indicating that "b" was too low. Again n_p (Step 3) was less than n_p (Step 1).

It was seen from the first two attempts at solution that "b" must be between 0.800 and 0.750 and "n_p" must be between 7.850 and 7.826. Hence, "n_p" was assumed to be 7.840 and "b", 0.770. These values yielded the following results:

K_{n_3} (Step 1) = 0.00802 n_p (Step 1) = 7.840

K_{n_3} (Step 4) = 0.00812 n_p (Step 3) = 7.834

As a check on the mechanics of the solution, summations of the gram atoms of H, O, and N were made with the following result:

Using equation (1),

$H = 2a + 2b + c + d = 8.001$ (an error of .001)

Using equation (2),

$O = a + c + 2e + f + g = 6.000$ (no error)

Using equation (3),

$N = g + 2h = 4.000$ (no error)

Hence, the third solution, based on an assumed "n_p" of 7.840 and "b" of 0.770, was shown to be the correct solution. Each component was determined to within ± 0.002 moles. No greater accuracy would be warranted since errors inherent in the values used for the heats of formation and for equilibrium constants are of this order of magnitude or larger.

PART III

SAMPLE CALCULATION OF PERFORMANCE PARAMETERS

In order to illustrate the methods used in calculating the results presented in this thesis, the performance parameters for the system consisting of a stoichiometric mixture of nitrogen tetroxide and hydrazine with one-half mole of hydrogen added are presented in detail. The equation for this reaction at an elevated temperature is:

$$\begin{aligned} N_2O_4 + 2\ N_2H_4 + 0.5\ H_2\ (l) = \\ a\ H_2O\ (g) + b\ H_2 + c\ OH + d\ H + e\ O_2 \\ + f\ O + g\ NO + h\ N_2 \end{aligned}$$

The calculations are based on the assumption that two gram molecular weights of hydrazine are present. This gives a total mass of reactants, m, of 157.06 grams.

Step A. Calculation of Chamber Temperature (Tc)

The first step in the calculation was to determine the adiabatic flame temperature in the chamber (T_c). This equilibrium reaction temperature is that temperature for which the heat released by the reaction ($Q_{av}^{T_c}$) equals the enthalpy rise of the components of the reaction ($\sum n_i\ \Delta H_{300}^{T_c}$). Since both quantities depend on the composition, the method used is as follows:

a). Chamber temperature was estimated to be 3200° K. Chamber pressure is, as assumed, 20.41 atm.

b). The composition was solved for 3200° K using the method outlined in Part II. ΔH_{300}^{3200} and Q_{av}^{3200} were computed. These results appear in Table B. It is seen that ΔH_{300}^{3200} is less than Q_{av}^{3200}, which showed that estimate of $T_c = 3200°$ K is too low.

c). Second estimate was 3300° K and (b) was repeated. The results for $T_c = 3300°$ K showed ΔH_{300}^{3300} is greater than Q_{av}^{3300}. T_c is therefore between 3200° K and 3300° K.

d). A linear interpretation of both Q_{av} and ΔH was used to find ΔT where

$$T_c = 3200 + \Delta T$$

This double interpolation can be expressed as:

$$\Delta H_{300}^{3200} + \frac{\Delta T}{100}(\Delta H_{300}^{3300} - \Delta H_{300}^{3200}) = Q_{av}^{3200} + \frac{\Delta T}{100}(Q_{av}^{3300} - Q_{av}^{3200})$$

Substituting values from Table B,

$$216.84 + \frac{\Delta T}{100}(225.92 - 216.84) = 224.75 + \frac{\Delta T}{100}(210.70 - 224.75)$$

$\Delta T = 34°$ K

e). For use in subsequent calculations the composition at the chamber temperature, n_p^{3234}, and ΔH_{300}^{3234} were computed at this point. The composition at 3234° K was obtained by linear interpolation of the compositions at 3200° K and at 3300° K.

TABLE B

RESULTS OF SAMPLE CALCULATION OF CHAMBER TEMPERATURE

T (^{o}K)	3200	3300	3234
a	3.518	3.368	3.468
b	0.770	0.685	0.728
c	0.270	0.344	0.295
d	0.153	0.211	0.173
e	0.057	0.076	0.064
f	0.033	0.052	0.039
g	0.064	0.084	0.071
h	2.968	2.958	2.965
n_p	7.834	7.948	7.874
ΔH_{300}^{T}	216.84 k cal	225.92 k cal	219.83 k cal
Q_{av}^{T}	224.75 k cal	210.70 k cal	219.93 k cal

where $\Delta H_{300}^{T} = \sum_{i=a}^{h} (\text{moles of component})_i \times (\Delta H_{300}^{T} \text{ of component})_i$ (21)

$Q_{av}^{T} = Q_f$ (products) - Q_f (reactants) (22)

Table II lists values of ΔH_{300}^{T} for each component versus temperature.

Table III lists values of heats of formation of the various components used in evaluating Q_{av}^{T} of the chamber and exhaust gases and of the reactants.

Step B. Calculation of Characteristic Velocity (c*)

At this point the characteristic velocity, c*, was computed. This parameter is a measure of the combustion efficiency and is a function only of the propellant properties, chamber combustion conditions, and nozzle conditions from the chamber to the throat.

By definition,

$$c^* = \frac{P_c f_t}{\dot{m}} \tag{23}$$

By substitution in (23),

$$c^* = \frac{a_c}{\Gamma'(\gamma_c)} = \frac{1}{\Gamma'(\gamma_c)}\sqrt{\frac{\gamma_c\, g\, R_u\, T_c}{\overline{M}_c}} \tag{24}$$

By substituting the proper values of "g", "R_u", and the necessary conversion factors, (24) becomes:

$$c^* = \frac{946.01}{\Gamma'(\gamma_c)}\sqrt{\frac{\gamma_c\, T_c}{10\, \overline{M}_c}}\ \text{ft sec}^{-1} \tag{25}$$

if T_c is expressed in degrees Kelvin and $\overline{M}_c$, in grams/mol.

In arriving at equation (24) from (23) only one assumption is necessary. The ratio of specific heat capacities of the products of reaction is assumed to be constant from the chamber to the nozzle throat and equal to γ_c; γ_c being the ratio of the specific heat capacities of the products of reaction at the equilibrium chamber temperature. This is a reasonably good assumption. The pressure changes markedly from the chamber to the throat; but the temperature, and consequently, γ , changes only slightly.

In order to use (25), $\overline{M}_c$, γ_c, and $\Gamma'(\gamma_c)$ were computed. The average molecular weight of the products of reaction at equilibrium chamber temperature was obtained first. The weight of reactants (m) was chosen to be 157.06 grams and the number of moles of chamber products was computed in Step A.

$$\overline{M}_c = \frac{m}{n^{T_c}} \tag{26}$$

$$\overline{M}_c = \frac{157.06 \text{ gms}}{7.874 \text{ moles}} = 19.948 \text{ gm mol}^{-1}$$

The isobaric heat capacity of the products of reaction was found by considering the enthalpy change of the products of reaction with the system in equilibrium over the 100° K temperature range nearest T_c. This enthalpy change was then divided by the product of the average number of moles present in the chamber and the temperature range (100° K) to give $(C_p)_c$. In this calculation,

$$(C_p)_c = \frac{\delta H_{3200}^{3300}}{\overline{n}_p(100^\circ \text{ K})} \tag{27}$$

where $\delta H_{3200}^{3300} = (\Delta H_{300}^{3300} - \Delta H_{300}^{3200}) + (Q_{av}^{3200} - Q_{av}^{3300})$

$$\overline{n}_p = \frac{n^{3200} + n^{3300}}{2}$$

Substituting numerical values from Table B, Step A,

$$\delta H_{3200}^{3300} = (225.92 - 216.84) \text{ k cal} + (224.75 - 210.70) \text{ k cal}$$

$$= 23.13 \text{ k cal}$$

$$\overline{n}_p = \frac{(7.834 + 7.948)}{2} \text{ moles}$$

$$= 7.891 \text{ moles}$$

Using (24),

$$(C_p)_c = \frac{23.13 \times 10^3 \text{ cal}}{7.891 \text{ moles} \times 100^\circ \text{ K}}$$

$$= 29.312 \text{ cal mol}^{-1} \, {}^\circ\text{K}^{-1}$$

$$\gamma_c = \frac{(C_p)_c}{(C_v)_c} = \frac{(C_p)_c}{(C_p)_c - R_u} \tag{28}$$

$$= \frac{29.312 \text{ cal mol}^{-1} \, {}^\circ\text{K}^{-1}}{(29.312 - 1.986) \text{ cal mol}^{-1} \, {}^\circ\text{K}^{-1}}$$

$$\gamma_c = 1.073$$

The function Γ' can be represented by the following linear equation:

$$\Gamma' = .1047 + .5048 \, \gamma \tag{29}$$

Using (29),

$$\Gamma'(\gamma_c) = .1047 + .5048 \, (1.073)$$

$$= .6463$$

Repeating (25),

$$c^* = \frac{946.01}{\Gamma'(\gamma_c)} \sqrt{\frac{\gamma_c \, T_c}{10 \, \bar{M}_c}} \text{ ft sec}^{-1}$$

$$= \frac{946.01}{.6463} \sqrt{\frac{1.073 \times 3234}{10 \times 19.948}} \text{ ft sec}^{-1}$$

$$c^* = 6105 \text{ ft sec}^{-1}$$

Step C. Calculation of Equilibrium Exhaust Temperature (T_e)

The calculation of the chamber temperature assumed that the reactants in the chamber completely reacted and that they remained in the chamber for a sufficient time to permit the establishment of equilibrium concentrations of all the components. When the gases leave the chamber and flow through the nozzle, there are two mechanisms assumed possible. Either the composition of the gas mixture remains constant as it flows through the nozzle, or the composition is changing continuously in accordance with the pressure variations, temperature variations, and the corresponding equilibrium constants. In reality, some intermediate state is probably maintained between these two extremes.

In calculating T_e it will first be assumed that equilibrium flow conditions exist in the nozzle as well as in the chamber. At the end of the calculation it will be pointed out what modifications were applied to this method in order to compute the parameters assuming constant composition flow.

Since isentropic flow is assumed, the exhaust temperature (T_e) can be calculated from the following equation:

$$T_e = T_c \left[\frac{P_e}{P_c}\right]^{\frac{\bar{\gamma}-1}{\bar{\gamma}}} = T_c \left[\frac{P_e}{P_c}\right]^{\frac{R}{\bar{C}_p}} \tag{30}$$

where

$$\bar{C}_p = \frac{\delta H_{T_e}^{T_c}}{\bar{n}_p \left(T_c - T_e\right)} \text{ cal mol}^{-1} \, {}^{\circ}\text{K}^{-1} \tag{31}$$

The correct T_e can be calculated by the following trial and error method.

1. Estimate T_e.
2. Using this estimated T_e evaluate $\delta H_{T_e}^{T_c}$ and $\bar{n}_p$.
3. Use Equation (31) to evaluate $\bar{C}_p$ and then use Equation (30) to calculate T_e.

4. The correct solution is obtained when the calculated value is equal to, or closely approximates the estimated value. In the calculations presented herein, the calculated T_e was accepted as correct when it was within ten degrees of the estimated value.

The detailed computation of T_e appears in Table C. The final result, $T_e = 2270\ ^{o}K$, was arrived at by the following procedure.

a) Exhaust temperature was estimated to be 2200^{o} K. Using method outlined in Part II, the composition was solved for 2200^{o} K and a total pressure of $P_e = 1$ atmosphere.

b) With the composition known, ΔH_{300}^{2200} and $\Delta Q_{av_{T_e}}^{T_c}$ were calculated.

$$\Delta Q_{av_{2200}}^{3234} = Q_{av}^{2200} - Q_{av}^{3234}$$

ΔH_{300}^{3234} was computed in Step A.

c) The total enthalpy change of the products of reaction that occurs between chamber and exhaust was computed using the following formula:

$$\delta H_{2200}^{3234} = (\Delta H_{300}^{3234} - \Delta H_{300}^{2200}) + \Delta Q_{av_{2200}}^{3234}$$

d) The average number of moles of reaction products that are present as the gas flows from the chamber to the exit was found.

$$\bar{n}_p = \frac{n_p^{3234} + n_p^{2200}}{2}$$

e) Equations (30) and (31) were then used to compute $\bar{C}_p$ and Te.

TABLE C

RESULTS OF SAMPLE CALCULATION OF EXHAUST TEMPERATURE

$T(^{\circ}K)$	3234 (T_c)	2200	2300
a	3.468	3.985	3.969
b	0.798	0.503	0.510
c	0.295	0.012	0.024
d	0.173	0.011	0.019
e	0.064	0.000	0.002
f	0.039	0.000	0.001
g	0.071	0.003	0.002
h	2.965	2.998	2.999
n_p	7.874	7.512	7.526
ΔH_{300}^{T}	219.83	132.25	140.40
$\Delta Q_{av_T}^{3234}$	0.00	44.94	43.44

Solution	1	2	3
T_e(est)	2200	2260	2270
ΔH_{300}^{3234}	219.83	219.83	218.83
$\Delta H_{300}^{T_e}$	132.25	137.14	137.96
$\Delta Q_{av_{T_e}}^{3234}$	44.94	44.04	43.89
$\delta H_{T_e}^{3234}$	132.62	126.83	125.86
$\bar{n}_p$	7.693	7.697	7.697
$T_c - T_e$	1034	974	964
$\bar{C}_p$	16.673	16.917	16.962
T_e	2257	2270	2270

Repeating (31),

$$\overline{C}_p = \frac{\delta H_{2200}^{3234}}{\overline{n}_p\,(Tc - Te)} \quad \text{cal mol}^{-1}\ {}^{\circ}K^{-1}$$

$$= \frac{132.62 \times 10^3 \text{ cal}}{7.693 \text{ moles} \times (3234 - 2200)^{\circ}K}$$

$$\overline{C}_p = 16.673 \text{ cal mol}^{-1}\ {}^{\circ}K^{-1}$$

And using (30),

$$Te = Tc \left[\frac{Pe}{Pc}\right]^{\frac{R}{\overline{C}p}}$$

$$= 3234^{\circ}\ K \left[\frac{1 \text{ atm}}{20.41 \text{ atm}}\right]^{\frac{1.986}{16.673}}$$

$$Te = 2257^{\circ}\ K$$

f) The next estimate of exhaust temperature was 2260° K. Since this estimate was not an even hundred degree value, the following were calculated prior to repeating (b), (c), (d), and (e): Composition at 2300° K, ΔH_{300}^{2300}, and $\Delta Q_{av_{2300}}^{3234}$.

g) The procedure outlined in (b), (c), (d) and (e) was repeated for the new estimate of $T_e = 2260^{\circ}$ K. Linear interpolation between 2200° K and 2300° K values was used in determining ΔH_{300}^{2260}, $\Delta Q_{av_{2260}}^{3234}$, and n_p^{2260}.

h) This second attempt at solution yielded $T_e = 2270$. The variation from the estimated value was on the borderline of the accuracy standards set up for the calculations so a third solution was made using an estimated $T_e = 2270^{\circ}$ K. This gave a calculated exhaust temperature of the same value. Hence, the correct T_e was taken to be 2270° K.

It should be noted at this point that $\delta H_{T_e}^{T_c}$ is required for the calculation of the effective exhaust velocity and must be calculated using the exact exhaust temperature, not using a temperature within ten degrees of the correct exhaust temperature. Therefore, when the calculated and estimated exhaust temperatures were not exactly the same value, a reevaluation of $\delta H_{T_e}^{T_c}$ was made using the correct value of the exhaust temperature for use in evaluating the effective exhaust velocity.

Step D. Calculation of Equilibrium Exhaust Velocity (c) and Equilibrium Specific Impulse (I_{sp})

The effective exhaust velocity was computed from the following formula:

$$c = \sqrt{\frac{2 \, \delta H_{T_e}^{T_c} \, J}{m}} \qquad (32)$$

where J is the mechanical equivalent of heat.

In obtaining Equation (32) it was assumed that:

1) The products of reaction behave as perfect gas.
2) The expansion process in the nozzle is adiabatic.
3) The velocity of the gases in the chamber is so small in comparison with "c" that it can be set equal to zero.

By substituting the proper value of J, and the necessary conversion factors (32) becomes:

$$c = 9493.2 \sqrt{\frac{\delta H_{T_e}^{T_c}}{m}} \quad \text{ft sec}^{-1} \qquad (33)$$

if $\delta H_{T_e}^{T_c}$ is expressed in kilocalories and "m" in grams.

The $\delta H_{T_e}^{T_c}$ was computed in Step C and m was chosen arbitrarily at the beginning of the calculation. Substitution in (33) gives:

$$c = 9493.2 \sqrt{\frac{125.86}{157.07}} \text{ ft sec}^{-1}$$

$$c = 8497 \text{ ft sec}^{-1}$$

The specific impulse is expressed by the following relationship:

$$I_{sp} = \frac{c}{g} \tag{34}$$

$$= \frac{8497 \text{ ft sec}^{-1}}{32.2 \text{ ft sec}^{-2}}$$

$$I_{sp} = 263.9 \text{ sec}$$

Step E. Calculation of Nozzle Thrust Coefficient (C_F) and Average Molecular Weight of Reaction Products

A nozzle thrust coefficient is defined by the following relationship:

$$C_F = \frac{F}{P_c f_t} \tag{35}$$

Expressing the effective exhaust velocity in terms of the thrust and mass flow rate, it is seen that

$$c = \frac{F}{\dot{m}} = \frac{F/P_c f_t}{\dot{m}/P_c f_t} = \frac{C_F}{c^*}$$

or

$$C_F = \frac{c}{c^*} \tag{36}$$

$$C_F = \frac{8497 \text{ ft sec}^{-1}}{6105 \text{ ft sec}^{-1}}$$

$$C_F = 1.39$$

The average molecular weight of the reaction products during their passage through the nozzle was computed from the relationship,

$$\bar{M} = \frac{m}{\bar{n}_p} \qquad (37)$$

where $\bar{n}_p = \dfrac{n_p^{3254} + n_p^{2270}}{2}$

$$= \frac{7.674 + 7.520}{2} \text{ moles}$$

$$\bar{n}_p = 7.697 \text{ moles}$$

$$\bar{M} = \frac{157.07 \text{ gm}}{7.697 \text{ moles}}$$

$$= 20.407 \text{ gm mol}^{-1}$$

Step F. Calculation of Altitude Index (h)

The determination of altitude index was made from a set of curves which weighted the specific impulse and mean propellant density in a manner believed more properly than given by density-impulse. This altitude index is for a large rocket manufactured and operated under a given set of assumed conditions.

The mean propellant density ($\bar{\rho}$) was calculated.

$$\bar{\rho} = \frac{M}{\text{Volume}}$$

$$= \frac{157.07 \text{ gms}}{139.56 \text{ cm}^3}$$

$$\bar{\rho} = 1.13 \text{ gm cm}^{-3}$$

The values of the densities used to determine the total volume occupied by this mass of liquid propellants are listed in Table IV.

From Step D, I_{sp} = 263.9 sec. Using this I_{sp} and the $\bar{\rho}$ calculated above as entering arguments to the curve, the altitude index was found to be 536 miles.

For the case of constant composition flow, the chamber temperature (T_c) and the characteristic velocity (c^*) are computed exactly as outlined in Steps A and B, since these quantities are independent of the type of flow in the nozzle.

In calculating the exhaust temperature (T_e) in Step C, the composition of the gas mixture was held fixed at the composition that prevailed at the equilibrium chamber temperature and the changes in the resulting heat balances made. As a result of this constant composition, $\Delta Q_{av}{}_{T_e}^{T_c}$ will vanish and $\delta H_{T_e}^{T_c}$, $\bar{C}_p$ and T_e will be lower than the values obtained assuming equilibrium flow.

With these exceptions the remaining calculations are similar to those for the case of equilibrium flow. However, the values obtained in Steps D, E, and F will differ from those obtained in the equilibrium flow calculations since they depend on $\delta H_{T_e}^{T_c}$ and $\bar{n}_p$ calculated in Step C. The characteristic exhaust velocity (c), specific impulse (I_{sp}), nozzle thrust coefficient (C_F), and the altitude index (h) are all less than the corresponding values obtained assuming equilibrium flow. The average molecular weight of the reaction products (II) is greater than the corresponding equilibrium flow value.

PART IV

DISCUSSION OF RESULTS

The performance parameters of the three bipropellant systems in stoichiometric proportions, which were used as the basis of the tripropellant systems studied in this thesis, were known earlier (Cf. Refs. 9, 11, and 12) although corrections were made to the hydrogen peroxide-hydrazine system. These corrections were made since earlier calculations of the performance parameters of the hydrogen peroxide-hydrazine system (Cf. Ref. 9) neglected molecular and atomic oxygen as components of the combustion gas mixture. All three systems investigated exhibit relatively high performance and, as such, they hold promise for future development and are currently of interest.

The problem of determining what effect the addition of hydrogen or ammonia would have on each of these systems was investigated by calculating the performance parameters for two series of tripropellant systems. The first series consisted of the stoichiometric mixture of the bipropellant system, to which was added increasing amounts of hydrogen; the second series, the stoichiometric mixture of the bipropellant system, to which was added increasing amounts of ammonia. For each system all the parameters illustrated in Part III were calculated for both equilibrium and constant composition flow conditions. The results are tabulated in Tables V-XVI and are presented graphically in Figures 1-16.

For each tripropellant system studied the following results are presented: a table of all parameters computed assuming equilibrium flow conditions, a table of all parameters computed assuming constant composition flow conditions, a graph of chamber temperature, exhaust temperature, specific impulse, and altitude index versus weight per cent of third component for both equilibrium and constant composition flows, and a graph of the percentage variations of these same parameters with weight per cent of third component.

The graphs of the percentage variations of certain of the parameters were prepared in order to better illustrate the relative effect of the third component on the various parameters. These graphs are based on the ratio of the parameter for a given percentage additive to the value of the parameter for the stoichiometric mixture of the bipropellant system. By referring to these curves for any particular system one can tell what the effect on the chamber temperature, the exhaust temperature, specific impulse and altitude index will be for a given weight per cent of third component - all in terms of a percentage of the value of the parameter before the addition of a third component.

At the first inspection of a plot of percentage variation of parameters with weight per cent of third component, it may appear that the constant composition value of the parameter is greater than the corresponding equilibrium value. It should be realized that although the percentage of the stoichiometric value may be greater for constant composition flow, the absolute value of the parameter for equilibrium flow is always greater than, or at least equal to, the value for constant composition flow.

A. ADDITION OF LIQUID HYDROGEN TO A STOICHIOMETRIC MIXTURE OF NITROGEN TETROXIDE AND HYDRAZINE.

Of the three basic bipropellant systems the best performance is shown by the nitrogen tetroxide-hydrazine system (Cf. Ref. 11). Its chamber temperature at the stoichiometric mixture ratio is 3233° K. Assuming equilibrium flow conditions the exhaust temperature is 2334° K, the specific impulse is 259.2 seconds, and the altitude index is 525 miles. Corresponding values for constant composition flow are 1823° K, 247.5 seconds, and 472 miles, respectively. These values are for the parameters at the stoichiometric mixture ratio and are the basis for the comparisons presented in succeeding paragraphs.

The chamber temperature, exhaust temperature, specific impulse, and altitude index for both equilibrium and constant composition flow conditions versus the weight per cent of liquid hydrogen in the tripropellant system are presented in Figure 1. Figure 2 is a graphical presentation of the percentage variation of the same parameters as plotted in Figure 1 versus weight per cent of liquid hydrogen.

The values of all parameters computed as well as the percentage variations plotted in Figure 2 are listed in Table V for equilibrium flow and in Table VI for constant composition flow.

Figure 2 shows that the greatest effects of the hydrogen addition are seen in the changes of the exhaust temperature and the chamber temperature. For equilibrium flow the exhaust temperature decreases steadily with increasing hydrogen. For the system containing maximum hydrogen, 16.23%, an exhaust temperature of 809° K is only 34.7% of the stoichiometric value, 2334° K. The effect on the exhaust temperature for constant composition flow is not quite as great. At the point of maximum hydrogen addition the exhaust temperature of 809° K is 44.4% of the stoichiometric value, 1823° K. The chamber temperature varies with hydrogen addition in the same general manner as the exhaust temperature. The effect, however, is not as pronounced as it is on the exhaust temperature. The maximum effect is at the point of the greatest hydrogen addition where the chamber temperature is still 1692° K, 52.3% of the stoichiometric value, 3233° K.

Thus, it can be seen that the effect on the chamber and exhaust temperatures is very desirable and appreciable. The next considerations are the corresponding effects on the performance parameters. It can be seen from Figure 2 that the effect on the specific impulse is also desirable. The addition of hydrogen increases the specific impulse which reaches its maximum near the point corresponding to 9.0% hydrogen. For equilibrium flow the maximum is 275.6 seconds, 106.5% of the equilibrium stoichiometric specific impulse, 259.2 seconds. For constant composition flow the maximum is 275.4 seconds, 111.0% of the constant composition stoichiometric value, 247.5 seconds. Both curves are very flat, varying less than 2.5% in the range of hydrogen from 5 to 16%.

The effect on the altitude index is somewhat different. Again referring to Figure 2, it is seen that for low values of hydrogen the initial effect is to increase the altitude index. The maximum is soon reached, and then the altitude index decreases in much the same manner as the temperatures because of a rapidly declining mean bulk density. For equilibrium flow the maximum, 536 miles, 102.1% of the stoichiometric value, 525 miles, is reached at 0.64% hydrogen. The constant composition flow maximum, 496 miles, 105.1% of the stoichiometric altitude index, 472 miles, is reached at 2.5% hydrogen. From these maximum values the altitude index decreases steadily and for the system containing 16.23% hydrogen, the values are 330 miles, 62.9% of the stoichiometric value for equilibrium flow and 330 miles, 70.0% of the stoichiometric value for constant composition flow.

In spite of the decrease in altitude index, the overall effect is still desirable since the percentage decrease in chamber temperature is greater than the corresponding percentage decrease in altitude index. In practice the two factors would have to be carefully weighted depending on the use to which the missile is to be put. For hydrogen addition greater than 3%, the percentage decrease in altitude index lags the percentage decrease in chamber temperature by 4 to 10% for equilibrium flow; for constant composition flow, by 11 to 18%.

The characteristic velocity varies in almost the exact manner in which the effective exhaust velocity and specific impulse vary. This can be seen by examining the variation in thrust coefficient, the ratio of effective exhaust velocity to the characteristic velocity. For equilibrium flow it varies from 1.40 at stoichiometric to 1.38 for maximum hydrogen. This is less than 2% variation. For constant composition the variation is slightly greater, from 1.34 to 1.38, or about 3%.

B. ADDITION OF LIQUID AMMONIA TO A STOICHIOMETRIC MIXTURE OF NITROGEN TETROXIDE AND HYDRAZINE.

The results for the system, nitrogen tetroxide-hydrazine with liquid ammonia added, are presented in Table VII, Table VIII, Figure 3, and Figure 4. For purposes of discussing this system, Figure 4, the percentage variation curve, will be used.

As in the previous system discussed, the greatest effects of the third component are on the temperatures.

The chamber temperature and exhaust temperatures decrease steadily with increasing ammonia. At the point of maximum ammonia addition, corresponding to 17.91% by weight, the temperatures are: chamber temperature, 2628° K, 81.3% of the stoichiometric value, 3233° K; exhaust temperature for equilibrium flow, 1456° K, 62.4% of the stoichiometric value, 2334° K; and exhaust temperature for constant composition flow, 1434° K, 78.7% of the stoichiometric value, 1823° K.

The specific impulse, assuming equilibrium flow, decreases slowly with increasing ammonia and for the maximum ammonia content, the specific impulse is 244.6 seconds, 94.4% of the stoichiometric value, 259.2 seconds. For constant composition flow the specific impulse increases to a maximum of 250.8 seconds, 101.3% of the stoichiometric value, 247.5 seconds, near 5% ammonia. It then decreases to 242.7 seconds, 98.1% of the stoichiometric value, at 17.91% ammonia.

Similar tendencies are shown in the variation of the altitude index. For equilibrium flow the altitude index is almost constant from 0 to 4% ammonia and then drops off to 439 miles, 83.6% of the stoichiometric value, 525 miles, at maximum ammonia content. For constant composition flow the altitude index increases to a maximum of 483 miles, 102.3% of the stoichiometric value, 472 miles, near 5% ammonia. It then decreases to 424 miles, 89.8% of the stoichiometric, at the point of maximum ammonia.

As in the system in which hydrogen was added, the variation in the thrust coefficient is very small indicating that the characteristic velocity varies in almost the same manner as the specific impulse.

C. GENERAL RESULTS APPLICABLE TO ALL SYSTEMS INVESTIGATED.

Two systems have been discussed in detail. Similar discussions of the other four systems studied would not be very dissimilar although numerical results are not identical. The results of all six systems are presented in Tables V to XVI and in Figures 1 to 16. A study of these results makes possible certain generalizations to all the systems investigated.

When the per cent variation of chamber temperature, exhaust temperature, specific impulse and altitude index are plotted versus weight per cent of third component, hydrogen or ammonia, the following can be said of these curves for all systems considered.

1. The parameter that is affected to the greatest extent is the exhaust temperature for equilibrium flow.
2. With the exception of the red fuming nitric acid-ammonia-hydrazine system, the parameter that is affected to the next greatest extent is the exhaust temperature for constant composition flow.

3. With the exception of the red fuming nitric acid-ammonia-hydrazine system the parameter that is affected to the next greatest extent is the chamber temperature. Both 2 and 3 are also true for ammonia addition of greater than 6% to the red fuming nitric acid-ammonia-hydrazine systems.
4. Next in order is the altitude index for equilibrium flow. However, there are several minor irregularities in this order for weight per cents of third component of less than 2%.
5. If the altitude index for constant composition flow is neglected for the time being, the parameter which maintains the highest percentage of its stoichiometric value is the specific impulse for constant composition flow. Just below this is the specific impulse for equilibrium flow.
6. The altitude index for constant composition flow behaves quite differently with the addition of liquid hydrogen or liquid ammonia. This occurs because of the large difference in the densities of the two liquids. Liquid hydrogen has a density of .07 grams per cubic centimeter while liquid ammonia has a density of .648 grams per cubic centimeter. For hydrogen addition of greater than 3%, the

altitude index for constant composition flow is below the curve of the specific impulse variation. For ammonia addition this parameter remains above the specific impulse curve for constant composition flow out to a point where the ammonia addition is between 8.5% and 11%, depending on the system.

The main purpose of the addition of a third component is to reduce the chamber temperature. However, with this change of temperature and the presence of increasing quantities of a third component, the performance changes. In an attempt to determine parameters which can be used as a measure of the effectiveness of the addition of the third component, the percentage variation curves were considered, and from them the following quantities were computed for all systems for both equilibrium and constant composition flows:

$E_{(I_{sp})}$ defined as $(I_{sp}/I_{sp}^{o} - T_c/T_c^{o})$

$E_{(h)}$ defined as $(h/h^{o} - T_c/T_c^{o})$

The superscript zero represents the value of the parameter for the stoichiometric mixture ratio before the addition of a third component. It was found that the value of each of these parameters was practically constant for equal percentages of hydrogen in the three systems. The same was found to be true for equal percentages of ammonia for the ammonia containing systems.

These values were averaged for the hydrogen systems and for the ammonia systems. The average error in the value of $E_{(I_{sp})}$ or $E_{(h)}$ for any system, when compared with the mean value of the parameter for the three systems, was found to be small as can be seen from the following results for the nitrogen tetroxide-hydrogen-hydrazine system.

Flow	Parameter	Av. Error	Max. Error
Equilibrium	$E_{(I_{sp})}$	0.004	0.008
Constant Composition	$E_{(I_{sp})}$	0.015	0.021
Equilibrium	$E_{(h)}$	0.006	0.007
Constant Composition	$E_{(h)}$	0.027	0.030

This order of magnitude of the average and maximum errors was the same for the other systems.

The values of these parameters are listed in Tables XVII to XXIV. Figure 17 is a plot of the average values of the four quantities, $E_{(I_{sp})}$ and $E_{(h)}$ for both types of flow, versus weight per cent of hydrogen or ammonia. A study of Tables XVII to XXIV and Figure 17 makes several general results apparent.

For equal weight per cents of hydrogen, the per cent lag of the specific impulse or altitude index behind the per cent variation in chamber temperature is the same within ± 3% for all three hydrogen tripropellant systems studied. This is also true for equal percentages of ammonia in the three ammonia tripropellant systems investigated.

The obvious usefulness of these relatively simple parameters lies, of course, in their ability to predict performances of tripropellant systems once the chamber temperature curves have been calculated or estimated, and as an indirect means for illustrating the relative merit of a series of third components under consideration as possible coolants.

The parameter, $E_{(I_{sp})}$, was applied to data from other sources in so far as it was available. It is shown in Table XVIII that $E_{(I_{sp})}$, calculated from data for constant composition flow conditions for the liquid oxygen-liquid hydrogen-hydrazine system (Cf. Ref. 3), was in good agreement with these results. The average error was .016. This was the only other data available for a tripropellant system containing hydrogen, nitrogen and oxygen.

Using data for carbonaceous tripropellant systems (Cf. Ref. 4), it was found that agreement among the carbonaceous systems was satisfactory, but that $E(I_{sp})$ for systems containing carbon was not in agreement with $E(I_{sp})$ for those tripropellant systems containing only hydrogen, nitrogen and oxygen. However, it is believed that similar parameters might be useful in analyzing carbonaceous systems at such time as more tripropellant data is available.

The relative effectiveness of hydrogen can be conveniently compared with that of ammonia on the basis of these parameters. If the variation of specific impulse is of primary importance, $E_{(I_{sp})}$ is the interesting parameter. For low percentage of hydrogen (say 4%) $E_{(I_{sp})}$ is about nine times greater than the corresponding $E_{(I_{sp})}$ for ammonia. At higher percentages the effect is less pronounced. For example, at 15% of hydrogen the $E(I_{sp})$ is about four times that for ammonia.

When the variation of altitude index is of primary importance as in the case of long range or high altitude missiles, hydrogen is also more effective than ammonia - based on a comparison of corresponding values of $E_{(h)}$. For 4% of hydrogen or ammonia the ratio of the $E_{(h)}$ for hydrogen to the $E_{(h)}$ for ammonia is eight. For 15% of third component the factor is still two.

REFERENCES

1. Duwez, Pol., and Wheeler, H. L. Jr., "Preliminary Experiments on the Sweat Cooling Method", Progress Report No. 3-13. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, July 18, 1946.

2. Zima, G. E., and Wheeler, H. L. Jr., "Sweat Cooling Tests with the 50 Lb. Thrust Rocket Motor", Progress Report No. 9-17. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, July 22, 1947.

3. Altman, D., "The Increase in Performance Resulting from the Addition of Hydrogen to a Hydrazine-Liquid Oxygen Propellant System", Progress Report No. 9-15. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, August 6, 1947.

4. Rice, H. E., "Performance Calculations of New Propellant Systems", Aeronautical Engineer Thesis, California Institute of Technology, June 1947.

5. Weissbluth, M., "Performance of Jet Motors Based on Theoretical Calculations with Special Reference to the Liquid Oxygen-Gasoline Propellant Combination", Progress Report No. 16. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, April 28, 1944.

6. Lutz, O., "Vergleichsbetrachtongen und Treibstofffragen bei R-Antriebe", Schriften Der Deutsche Akademie der Luftfahrtforschung, p. 21, 1943.

7. Noeggerath, W., "Thermodynamische Treibstoffuntersuchungen", Dissertation Techinsche Hochschule Braunschweig, 1939.

8. "Increase of Jet Engine Thrust by Water Injection", Hirth Motoren Stuttgart, Naval Air Material Center, Philadelphia, A.E.L. Translation No. 17 (Issued as BuAer CGD-448, June 22, 1945). Date of Original Report Unknown.

9. Stosick, A. J., "Performance Calculations for Propellants using Hydrogen Peroxide and Performance Calculations for Diethyleneglycol Dinitrate as a Monopropellant", Progress Report No. 1-25. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, April 2, 1945.

10. Stosick, A. J., "Liquid Propellants for Rockets", Progress Report No. 9-8. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, December 3, 1946.

11. Cole, Leland G., "Performance Calculations of Propellant Systems Employing Nitrogen Tetroxide", Progress Report No. 9-23. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, March, 1948.

12. Cole, Leland G., "Chamber Pressure and Its Effect on Theoretical Performance of the Systems RFNA-Hydrazine, RFNA-Hydrazine Hydrate, RFNA-Liquid Ammonia, and RFNA-Liquid Hydrogen", Progress Report No. 9-12. Pasadena: Jet Propulsion Laboratory, California Institute of Technology, March, 1948.

13. Bichowski, F. R., and Rossini, F. D., "The Thermochemistry of Chemical Substance", Reinhold Publishing Corporation (1936).

14. Department of Commerce, Circular of the National Bureau of Standards No. 142, "Tables of Thermodynamic Properties of Ammonia", Government Printing Office, Washington, D. C. April 16, 1923.

15. "Tables of Selected Values of Chemical Thermodynamic Properties", Department of Commerce, National Bureau of Standards and Office of Naval Research, U. S. N., March 31, 1947.

Table XXX. Equilibrium constants.*

Temp. (°K)	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}
298.1	1.007×10^{-5}	7.82×10^{24}		7.280×10^{2}	1.58×10^{24}					
700	0.1110	3.837×10^{3}		9.150×10^{-3}	1.08×10^{12}					
800	.2478	31.25		2.909×10^{-3}	9.64×10^{11}					
900	.4546	0.7513		1.177×10^{-3}	1.46×10^{11}					
1000	.7288	.03720		5.838×10^{-4}	3.29×10^{10}					
1100	1.058	3.147×10^{-3}		3.070×10^{-4}	9.55×10^{9}					
1200	1.435	3.994×10^{-4}		1.847×10^{-4}	3.39×10^{9}					
1300	1.844	6.875×10^{-5}		1.198×10^{-4}	1.40×10^{9}					
1400	2.270	1.553×10^{-5}		8.239×10^{-5}	6.56×10^{8}					
1500	2.704	4.218×10^{-6}		5.948×10^{-5}	3.38×10^{8}					
1600	3.135	1.348×10^{-6}		4.450×10^{-5}	1.89×10^{8}					
1700	3.555	4.925×10^{-7}		3.479×10^{-5}	1.13×10^{8}					
1800	3.975	2.029×10^{-7}		2.783×10^{-5}	7.08×10^{7}					
1900	4.393	9.211×10^{-8}		2.283×10^{-5}	4.66×10^{7}					
2000	4.782	4.545×10^{-8}	5.738×10^{-6}	1.923×10^{-5}	3.19×10^{7}	9.13×10^{-8}	2.08×10^{-7}	8.650×10^{-7}	1.629×10^{-3}	1.644×10^{-4}
2100	5.149	2.393×10^{-8}	1.495×10^{-5}	1.641×10^{-5}	2.26×10^{7}	3.45×10^{-7}	8.65×10^{-7}	2.440×10^{-6}	3.119×10^{-3}	3.699×10^{-4}
2200	5.420	1.320×10^{-8}	3.69×10^{-5}	1.421×10^{-5}	1.65×10^{7}	1.308×10^{-6}	3.34×10^{-6}	6.946×10^{-6}	5.610×10^{-3}	8.072×10^{-4}
2300	5.853	7.902×10^{-9}	8.39×10^{-5}	1.247×10^{-5}	1.24×10^{7}	4.19×10^{-6}	1.096×10^{-5}	1.560×10^{-5}	9.883×10^{-3}	1.587×10^{-3}
2400	6.140	4.873×10^{-9}	1.885×10^{-4}	1.107×10^{-5}	9.48×10^{6}	1.260×10^{-5}	3.305×10^{-5}	3.475×10^{-5}	1.992×10^{-2}	2.951×10^{-3}
2500	6.440	3.138×10^{-9}	3.512×10^{-4}	9.95×10^{-6}	7.40×10^{6}	3.452×10^{-5}	9.121×10^{-5}	7.231×10^{-5}	2.514×10^{-2}	5.230×10^{-3}
2600	6.668	2.089×10^{-9}	6.74×10^{-4}	9.00×10^{-6}	5.88×10^{6}	8.85×10^{-5}	2.34×10^{-4}	1.426×10^{-4}	3.937×10^{-2}	8.995×10^{-3}
2700	6.934	1.435×10^{-9}	1.189×10^{-3}	8.21×10^{-6}	4.74×10^{6}	2.08×10^{-4}	5.65×10^{-4}	2.678×10^{-4}	5.875×10^{-2}	1.462×10^{-2}
2800	7.155	1.018×10^{-9}	2.05×10^{-3}	7.56×10^{-6}	3.87×10^{6}	4.84×10^{-4}	1.243×10^{-3}	4.797×10^{-4}	8.165×10^{-2}	2.312×10^{-2}
2900	7.376	7.360×10^{-10}	3.42×10^{-3}	6.98×10^{-6}	3.21×10^{6}	9.90×10^{-4}	2.65×10^{-3}	8.360×10^{-4}	1.148×10^{-1}	3.556×10^{-2}
3000	7.582	5.458×10^{-10}	5.479×10^{-3}	6.49×10^{-6}	2.69×10^{6}	1.983×10^{-3}	5.336×10^{-3}	1.373×10^{-3}	0.1579	5.290×10^{-2}
3100	7.748		8.375×10^{-3}		2.27×10^{6}	3.803×10^{-3}	1.027×10^{-2}	2.210×10^{-3}	.2125	7.677×10^{-2}
3200	7.929		1.294×10^{-2}		1.94×10^{6}	7.039×10^{-3}	1.904×10^{-2}	3.452×10^{-3}	.2813	1.087×10^{-1}
3300	8.078		1.830×10^{-2}		1.66×10^{6}	1.248×10^{-2}	3.369×10^{-2}	5.233×10^{-3}	.3654	1.513×10^{-1}
3400	8.192		2.758×10^{-2}		1.44×10^{6}	2.142×10^{-2}	5.657×10^{-2}	7.798×10^{-3}	.4682	2.060×10^{-1}
3500	8.304	1.821×10^{-10}	3.894×10^{-2}	4.86×10^{-6}	1.26×10^{6}	3.583×10^{-2}	9.718×10^{-2}	1.182×10^{-2}	.5910	2.763×10^{-1}
3600	8.449		5.404×10^{-2}		1.10×10^{6}	5.821×10^{-2}	1.591×10^{-1}	1.611×10^{-2}	.7367	3.634×10^{-1}
3700	8.538		7.355×10^{-2}		9.68×10^{5}	9.086×10^{-2}	2.518×10^{-1}	2.240×10^{-2}	.9064	4.691×10^{-1}
3800	8.664		9.821×10^{-2}		8.58×10^{5}	1.412×10^{-1}	3.876×10^{-1}	3.066×10^{-2}	1.107	5.984×10^{-1}
3900	8.712		1.300×10^{-1}		7.64×10^{5}	2.134×10^{-1}	5.870×10^{-1}	4.166×10^{-2}	1.336	7.569×10^{-1}
4000	8.752	6.66×10^{-11}	1.693×10^{-1}	3.94×10^{-6}	6.83×10^{5}	3.157×10^{-1}	8.711×10^{-1}	5.544×10^{-2}	1.587	9.485×10^{-1}
4100	8.819		2.162×10^{-1}		6.12×10^{5}	4.528×10^{-1}	1.256	7.258×10^{-2}	1.893	1.164
4200	8.884		2.760×10^{-1}		5.52×10^{5}	6.319×10^{-1}	1.808	9.423×10^{-2}	2.226	1.428
4300	8.898		3.443×10^{-1}		5.01×10^{5}	9.139×10^{-1}	2.537	1.206×10^{-1}	2.598	1.730
4400	8.929		4.302×10^{-1}		4.51×10^{5}	1.263	3.508	1.528×10^{-1}	3.012	2.089
4500	8.957	3.38×10^{-11}	5.291×10^{-1}	3.38×10^{-6}	4.10×10^{5}	1.719	4.777	1.916×10^{-1}	3.470	2.478
4600	8.974		6.451×10^{-1}		3.74×10^{5}	2.307	6.431	2.379×10^{-1}	3.989	2.923
4700	8.984		7.799×10^{-1}		3.41×10^{5}	3.088	8.545	2.927×10^{-1}	4.520	3.432
4800	8.994		9.344×10^{-1}		3.12×10^{5}	4.015	11.21	3.570×10^{-1}	5.118	3.992
4900	9.003		1.113		2.85×10^{5}	5.220	14.50	4.321×10^{-1}	5.784	4.637
5000	9.013	2.02×10^{-11}	1.317	3.00×10^{-6}	2.63×10^{5}	6.693	18.77	5.109×10^{-1}	6.481	5.317

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* See next page for definitions of K_1, K_2 ....

Table XXX. [Concluded.]

Temp. (°K)	K_{11}	K_{12}	K_{13}	K_{14}	K_{15}	K_{16}	K_{17}
298.1							
400							3.976×10^{-5}
500							1.822×10^{-5}
600							1.026×10^{-5}
700							6.660×10^{-6}
800							4.724×10^{-6}
900							3.603×10^{-6}
1000	2.11×10^{-10}					2.220×10^{-15}	2.688×10^{-6}
1100							2.416×10^{-6}
1200							2.081×10^{-6}
1300							1.835×10^{-6}
1400							1.653×10^{-6}
1500	2.98×10^{-11}				2.77×10^{-6}	9.078×10^{-16}	1.510×10^{-6}
2000	1.13×10^{-11}				2.37×10^{-6}	7.290×10^{-16}	1.136×10^{-6}
2500	6.62×10^{-12}				2.23×10^{-6}	7.446×10^{-16}	9.87×10^{-7}
3000		8.27×10^{-8}	3.55×10^{-7}	1.90×10^{-4}	2.16×10^{-6}		9.93×10^{-7}
3500		3.80×10^{-7}	8.45×10^{-7}	7.61×10^{-4}	2.16×10^{-6}		9.89×10^{-7}
4000		1.20×10^{-6}	1.65×10^{-6}	2.15×10^{-3}	2.17×10^{-6}		9.88×10^{-7}
4500		2.92×10^{-6}	2.62×10^{-6}	4.80×10^{-3}	2.22×10^{-6}		9.87×10^{-7}
5000		5.96×10^{-6}	4.41×10^{-6}	9.09×10^{-3}	2.28×10^{-6}		9.88×10^{-7}

$K_1 = P_{CO}P_{H_2O}/P_{CO_2}P_{H_2}$; $K_2 = P_{CH_4}P_{H_2O}/P^3_{H_2}P_{CO}$; $K_3 = P_{NO}P_{H_2}/P^{1/2}_{N_2}P_{H_2O}$;

$K_4 = P_{NH_3}/P^{1/2}_{N_2}P^{3/2}_{H_2}$; $K_5 = P_{CO}/P^{1/2}_{O_2}$; $K_6 = P_{O_2}P^2_{H_2}/P^2_{H_2O}$;

$K_7 = P_OP_{H_2}/P_{H_2O}$; $K_8 = P_N/P^{1/2}_{N_2}$; $K_9 = P_H/P^{1/2}_{H_2}$; $K_{10} = P_{OH}P^{1/2}_{H_2}/P_{H_2O}$.

$K_{11} = P_{C_2H_2}P^2_{H_2O}/P^2_{CO}P^3_{H_2}$; $K_{12} = P_{CH}P_{H_2O}/P_{CO}P^{3/2}_{H_2}$;

$K_{13} = P_{CN}P_{CO_2}/P^2_{CO}P^{1/2}_{N_2}$; $K_{14} = P_{NH}/P^{1/2}_{N_2}P^{1/2}_{H_2}$;

$K_{15} = P_{HCN}P_{H_2O}/P_{CO}P^{3/2}_{H_2}P^{1/2}_{N_2}$; $K_{16} = P_{C_2N_2}P^2_{CO_2}/P^4_{CO}P_{N_2}$;

$K_{17} = P_{H_2CO}/P_{H_2}P_{CO}$.

TABLE XI

ENTHALPY TABLE

$\Delta H_{300°K}^{T°K}$ kcals/gram mole

T °K	H_2	H_2O	CO	CO_2	O_2	N_2	OH	NO	H,N,O	$R\Delta T$
300	0.0	0.0	0.0	0.0	0.0	0.0			0.0	0.0
400	0.695	0.811	0.699	0.942	0.721	0.697			0.497	0.199
500	1.393	1.641	1.404	1.970	1.447	1.399			0.993	0.397
600	2.093	2.496	2.125	3.072	2.203	2.112			1.490	0.596
700	2.796	3.380	2.862	4.232	2.981	2.840			1.987	0.795
800	3.502	4.292	3.615	5.441	3.778	3.582			2.484	0.993
900	4.212	5.234	4.388	6.692	4.594	4.343			2.981	1.192
1000	4.931	6.208	5.171	7.976	5.421	5.118	4.985	5.308	3.477	1.391
1100	5.657	7.211	5.973	9.291	6.278	5.907	5.725	6.133	3.974	1.589
1200	6.393	8.247	6.785	10.629	7.135	6.708	6.465	6.958	4.471	1.788
1300	7.138	9.317	7.606	11.989	7.990	7.520	7.233	7.800	4.967	1.986
1400	7.895	10.399	8.437	13.367	8.847	8.342	8.002	8.643	5.464	2.185
1500	8.664	11.519	9.275	14.760	9.704	9.173	8.783	9.499	5.961	2.384
1600	9.439	12.662	10.120	16.168	10.592	10.009	9.584	10.355	6.457	2.582
1700	10.226	13.821	10.972	17.587	11.481	10.854	10.390	11.221	6.954	2.781
1800	11.023	15.006	11.829	19.017	12.369	11.703	11.197	12.088	7.451	2.980
1900	11.828	16.206	12.689	20.455	13.257	12.558	12.015	12.957	7.947	3.178
2000	12.644	17.424	13.554	21.902	14.146	13.417	12.834	13.827	8.444	3.377
2100	13.466	18.656	14.423	23.358	15.041	14.279	13.645	14.700	8.941	3.576
2200	14.295	19.904	15.294	24.820	15.874	15.143	14.504	15.598	9.436	3.774
2300	15.132	21.171	16.169	26.290	16.859	16.013	15.360	16.480	9.935	3.973
2400	15.975	22.446	17.045	27.760	17.802	16.883	16.213	17.364	10.430	4.171
2500	16.827	23.733	17.923	29.242	18.717	17.758	17.090	18.248	10.928	4.370
2600	17.683	25.031	18.807	30.729	19.659	18.636	17.936	19.143	11.425	4.568
2700	18.542	26.338	19.691	32.218	20.601	19.516	18.807	20.038	11.921	4.767
2800	19.410	27.656	20.576	33.712	21.543	20.399	19.678	20.929	12.418	4.966
2900	20.282	28.987	21.464	35.211	22.486	21.284	20.563	21.823	12.915	5.165
3000	21.160	30.315	22.353	36.712	23.427	22.170	21.447	22.716	13.411	5.363
3100	22.041	31.658	23.242	38.222	24.384	23.058	22.335	23.617	13.908	5.562
3200	22.927	33.006	24.136	39.734	25.344	23.947	23.227	24.519	14.405	5.761
3300	23.818	34.362	25.029	41.244	26.308	24.837	24.121	25.421	14.901	5.959
3400	24.712	35.723	25.923	42.764	27.276	25.729	25.021	26.325	15.398	6.158
3500	25.611	37.092	26.818	44.281	28.247	26.622	25.920	27.229	15.894	6.356
3600	26.512	38.466	27.715	45.808	29.219	27.518	26.822	28.135	16.392	6.555
3700	27.416	39.845	28.613	47.332	30.198	28.412	27.730	29.041	16.889	6.754
3800	28.326	41.231	29.512	48.862	31.178	29.307	28.640	29.949	17.385	6.952
3900	29.236	42.619	30.412	50.394	32.164	30.205	29.552	30.856	17.882	7.151
4000	30.153	44.010	31.313	51.930	33.153	31.104	30.467	31.761	18.379	7.350
4100	31.069	45.413	32.215	53.471	34.139	32.006	31.390	32.692	18.875	7.548

SOURCE OF DATA:

"THERMODYNAMIC PROPERTIES OF PROPELLANT GASES", HIRSCHFELDER, CURTISS, McCLURE, AND OSBORNE. O.S.R.D. REPORT # 547

NOTE: FOR USE OF THIS TABLE IN CALCULATING THEORETICAL PROPELLANT PERFORMANCE
Cf: PROGRESS REPORT 1-24

TABLE III

HEATS OF FORMATION USED IN THIS INVESTIGATION

$H_2(l)$	1.848[a]	k cal mol^{-1}
H_2O_2	44.516[b]	"
$N_2O_4(l)$	-12.2[c]	"
HNO_3	+41.66[c]	"
RFNA(6.8% N_2O_4	+41.05	"
N_2H_4	-12.05	"
$NH_3(l)$	+16.07[c]	"
$H_2O(g)$	+57.798	"
OH	-10.06	"
O	-59.159	"
H	-52.089	"
NO	-21.6[c]	"

[a] Calculated by L. G. Cole from data in Chemical Rubber Publishing Company Handbook of Chemistry and Physics, pp. 1745-1747 (1945).

[b] Chemical Rubber Publishing Company Handbook of Chemistry and Physics (1947).

[c] Bichowski, F. R., Rossini, F. D., "The Thermochemistry of Chemical Substances" Reinhold Publishing Corporation (1936).

All other data from "Tables of Selected Values of Chemical Thermodynamic Properties", National Bureau of Standards (U. S. Department of Commerce) with support of Office of Naval Research, USN, March 31, 1947.

TABLE IV

DENSITIES USED IN THIS INVESTIGATION

Component	ρ_f gm cm^{-3}
N_2H_4	1.01 at 15° C
H_2O_2	1.465 at 0° C
N_2O_4(1)	1.491 at 0° C
H_2(1)	0.07 at -252.8° C
NH_3(1)	0.648 at 20° C (Cf. Ref. 14)
HNO_3(6.8% N_2O_4)	1.545 at 20° C

TABLE V

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR N_2O_4-H_2(l)-N_2H_4 SYSTEM ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c^o	(5) T_e °K	(6) T_e/T_e^o	(7) $\overline{\rho}$ gm cm^{-3}	(8) $\overline{M}$
0.00	0.00	3233	1.000	2334	1.000	1.25	21.446
0.64	0.50	3234	1.000	2270	0.973	1.13	20.407
1.288	1.00	3208	0.992	2149	0.921	1.03	19.413
1.90	1.50	3158	0.977	2037	0.873	0.94	18.452
2.52	2.00	3099	0.959	1930	0.827	0.88	17.597
4.91	4.00	2809	0.869	1598	0.685	0.68	14.866
9.37	8.00	2283	0.706	1185	0.508	0.48	11.475
16.23	15.00	1692	0.523	809	0.347	0.33	8.468

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5965	8346	259.2	1.000	1.40	525	1.000
0.64	6105	8497	263.9	1.018	1.39	536	1.021
1.28	6198	8587	266.7	1.029	1.38	527	1.004
1.90	6264	8655	268.8	1.037	1.38	521	0.992
2.52	6303	8713	270.6	1.044	1.38	519	0.989
4.91	6390	8825	274.1	1.057	1.38	492	0.937
9.37	6413	8868	275.4	1.063	1.38	420	0.800
16.23	6337	8737	271.3	1.047	1.38	330	0.629

TABLE VI

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR N_2O_4-$H_2(l)$-N_2H_4 SYSTEM ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c^o	(5) T_e °K	(6) T_e/T_e^o	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	3233	1.000	1823	1.000	1.15	20.900
0.64	0.50	3234	1.000	1821	0.999	1.13	19.948
1.28	1.00	3208	0.992	1801	0.988	1.03	19.117
1.90	1.50	3158	0.977	1768	0.970	0.94	18.203
2.52	2.00	3099	0.959	1727	0.947	0.88	17.410
4.91	4.00	2809	0.869	1525	0.857	0.68	14.611
9.37	8.00	2283	0.706	1175	0.645	0.48	11.470
16.23	15.00	1692	0.523	809	0.444	0.33	8.466

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5965	7970	247.5	1.000	1.34	472	1.000
0.64	6105	8161	253.4	1.024	1.34	489	1.036
1.28	6198	8324	258.5	1.044	1.34	491	1.040
1.90	6264	8436	262.0	1.059	1.35	496	1.051
2.52	6303	8532	265.0	1.071	1.35	496	1.051
4.91	6390	8762	272.1	1.099	1.37	481	1.019
9.37	6413	8867	275.4	1.113	1.38	420	0.890
16.23	6337	8737	271.3	1.096	1.38	330	0.700

TABLE VII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR N_2O_4-NH_3(l)-N_2H_4 SYSTEM ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c^o	(5) T_e °K	(6) T_e/T_e^o	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	3233	1.000	2334	1.000	1.25	21.446
2.66	0.25	3208	0.992	2246	0.962	1.22	20.842
5.17	0.50	3161	0.978	2102	0.901	1.19	20.214
9.83	1.00	3017	0.933	1842	0.789	1.14	19.071
14.04	1.50	2830	0.875	1628	0.698	1.10	18.088
17.91	2.00	2628	0.813	1456	0.624	1.07	17.253

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5965	8346	259.2	1.000	1.40	525	1.000
2.66	6014	8375	260.1	1.003	1.39	527	1.004
5.17	6017	8343	259.1	0.999	1.39	523	0.996
9.83	5976	8229	255.6	0.986	1.38	498	0.949
14.04	5848	8073	250.7	0.967	1.38	472	0.899
17.91	5705	7875	244.6	0.944	1.38	439	0.836

TABLE VIII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR N_2O_4-$NH_3(l)$-N_2H_4 SYSTEM ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c°	(5) T_e °K	(6) T_e/T_e°	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	3233	1.000	1823	1.000	1.25	20.800
2.66	0.25	3208	0.992	1809	0.992	1.22	20.384
5.17	0.50	3161	0.978	1780	0.976	1.19	19.886
9.83	1.00	3017	0.933	1687	0.925	1.14	18.911
14.04	1.50	2830	0.875	1556	0.854	1.10	18.018
17.91	2.00	2628	0.813	1434	0.787	1.07	17.223

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}°	(14) C_F	(15) h mi.	(16) h/h°
0.00	5965	7970	247.5	1.000	1.34	472	1.000
2.66	6014	8039	249.6	1.008	1.34	479	1.015
5.17	6017	8076	250.8	1.013	1.34	483	1.023
9.83	5976	8065	250.5	1.012	1.35	479	1.015
14.04	5848	7996	248.3	1.003	1.37	460	0.975
17.91	5705	7816	242.7	0.981	1.37	424	0.898

TABLE IX

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR H_2O_2-H_2(l)-N_2H_4 SYSTEM ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c ^oK	(4) T_c/T_c^o	(5) T_e ^oK	(6) T_e/T_e^o	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	2851	1.000	1978	1.000	1.28	19.747
1.00	0.50	2843	0.997	1805	0.912	1.09	18.250
1.97	1.00	2749	0.964	1670	0.844	0.95	16.951
2.93	1.50	2639	0.926	1544	0.780	0.85	15.831
3.87	2.00	2527	0.886	1445	0.730	0.77	14.854
7.46	4.00	2140	0.751	1144	0.578	0.56	12.013
13.88	8.00	1628	0.571	798	0.403	0.38	8.938
23.21	15.00	1143	0.401	528	0.267	0.26	6.515

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5773	8067	250.5	1.000	1.40	491	1.000
1.00	5932	8221	255.3	1.019	1.39	487	0.992
1.97	5976	8290	257.5	1.028	1.39	475	0.967
2.93	6012	8349	259.3	1.035	1.39	462	0.941
3.87	6044	8396	260.7	1.041	1.39	456	0.929
7.46	6095	8461	262.8	1.049	1.39	409	0.833
13.88	6083	8396	260.7	1.041	1.38	326	0.664
23.21	5886	8128	252.4	1.008	1.38	227	0.462

TABLE X

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR H_2O_2-H_2(l)-N_2H_4 SYSTEM ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c°	(5) T_e °K	(6) T_e/T_e°	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	2851	1.000	1694	1.000	1.28	19.418
1.00	0.50	2843	0.997	1677	0.990	1.09	18.126
1.97	1.00	2749	0.964	1600	0.945	0.95	16.892
2.93	1.50	2659	0.926	1512	0.893	0.85	15.604
3.87	2.00	2527	0.886	1428	0.843	0.77	14.840
7.46	4.00	2140	0.751	1141	0.676	0.56	12.010
13.88	8.00	1628	0.571	798	0.471	0.38	8.838
23.21	15.00	1143	0.401	528	0.312	0.26	6.515

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}°	(14) C_F	(15) h mi.	(16) h/h°
0.00	5775	7852	243.8	1.000	1.36	458	1.000
1.00	5932	8107	251.8	1.033	1.37	474	1.035
1.97	5976	8234	255.7	1.049	1.38	468	1.022
2.93	6012	8320	258.4	1.060	1.38	458	1.000
3.87	6044	8365	259.8	1.066	1.38	455	0.993
7.46	6095	8459	262.7	1.078	1.39	409	0.893
13.88	6083	8396	260.7	1.069	1.38	326	0.712
23.21	5886	8128	252.4	1.035	1.38	227	0.496

TABLE XI

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR H_2O_2-NH_3(l)-N_2H_4 SYSTEM ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c ^oK	(4) T_c/T_c^o	(5) T_e ^oK	(6) T_e/T_e^o	(7) $\overline{\rho}$ gm cm^{-3}	(8) $\overline{M}$
0.00	0.00	2851	1.000	1979	1.000	1.28	19.747
4.08	0.25	2804	0.983	1767	0.893	1.23	18.851
7.84	0.50	2677	0.939	1606	0.812	1.19	18.049
14.54	1.00	2376	0.833	1342	0.678	1.12	16.719
20.32	1.50	2099	0.736	1140	0.576	1.07	15.698
25.38	2.00	1862	0.653	977	0.494	1.03	14.901

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5773	8067	250.5	1.000	1.40	489	1.000
4.08	5804	8035	249.5	0.996	1.38	479	0.980
7.84	5699	7922	246.0	0.982	1.39	460	0.941
14.54	5487	7648	237.5	0.948	1.39	419	0.857
20.32	5283	7351	228.3	0.911	1.39	371	0.759
25.38	5081	7048	218.9	0.874	1.39	333	0.681

TABLE XII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR H_2O_2-$NH_3(l)$-N_2H_4 SYSTEM ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1) WT%	(2) MOLAS	(3) T_c °K	(4) T_c/T_c°	(5) T_e °K	(6) T_e/T_e°	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	2851	1.000	1694	1.000	1.28	19.418
4.08	0.25	2804	0.983	1654	0.976	1.23	18.732
7.84	0.50	2677	0.939	1553	0.917	1.19	18.001
14.54	1.00	2376	0.833	1333	0.787	1.12	16.710
20.32	1.50	2099	0.736	1138	0.672	1.07	15.626
25.38	2.00	1862	0.653	977	0.577	1.03	14.901

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}°	(14) C_F	(15) h mi.	(16) h/h°
0.00	5773	7852	243.8	1.000	1.36	460	1.000
4.08	5804	7916	245.8	1.008	1.36	462	1.004
7.84	5699	7876	244.6	1.003	1.38	458	0.996
14.54	5487	7637	237.2	0.963	1.39	419	0.911
20.32	5283	7346	228.1	0.936	1.39	371	0.807
25.38	5081	7048	218.9	0.898	1.39	333	0.724

TABLE XIII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR RFNA-H_2(1)-N_2H_4 SYSTEM ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c^o	(5) T_e °K	(6) T_e/T_e^o	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	2957	1.000	2037	1.000	1.28	21.367
0.90	0.50	2949	0.997	1858	0.912	1.11	19.791
1.79	1.00	2856	0.966	1716	0.842	0.98	18.413
2.65	1.50	2746	0.929	1593	0.782	0.88	17.201
3.51	2.00	2632	0.890	1490	0.731	0.79	16.153
6.78	4.00	2229	0.754	1179	0.579	0.59	13.064
13.46	8.00	1660	0.568	816	0.401	0.40	9.693
21.43	15.00	1184	0.400	543	0.276	0.27	7.019

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5660	7870	244.4	1.000	1.39	460	1.000
0.90	5811	8028	249.3	1.020	1.38	468	1.017
1.79	5844	8107	251.8	1.030	1.39	458	0.996
2.65	5898	8160	253.4	1.037	1.38	449	0.976
3.51	5909	8193	254.4	1.041	1.39	436	0.948
6.78	5958	8245	256.1	1.048	1.38	386	0.839
13.46	5927	8179	254.0	1.039	1.38	313	0.680
21.43	5764	7889	246.0	1.002	1.38	212	0.461

TABLE XIV

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR RFNA-H_2(l)-N_2H_4 SYSTEM ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c^o	(5) T_e °K	(6) T_e/T_e^o	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	2957	1.000	1703	1.000	1.28	21.008
0.90	0.50	2949	0.997	1696	0.996	1.11	19.614
1.79	1.00	2856	0.966	1619	0.951	0.98	18.320
2.65	1.50	2746	0.929	1540	0.904	0.88	17.149
3.51	2.00	2632	0.890	1455	0.854	0.79	16.126
6.78	4.00	2229	0.754	1173	0.689	0.59	13.063
13.46	8.00	1680	0.568	816	0.479	0.40	9.693
21.43	15.00	1184	0.400	543	0.319	0.27	7.019

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5660	7636	237.2	1.000	1.35	437	1.000
0.90	5811	7882	244.8	1.028	1.36	447	1.023
1.79	5844	8022	249.1	1.046	1.37	447	1.023
2.65	5898	8096	251.4	1.055	1.37	441	1.009
3.51	5909	8155	253.3	1.063	1.38	430	0.984
6.78	5958	8244	256.0	1.075	1.38	386	0.883
13.46	5927	8179	254.0	1.066	1.38	313	0.716
21.43	5764	7889	245.0	1.030	1.38	212	0.485

TABLE XV

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR RFNA-$NH_3(l)$-N_2H_4 SYSTEM ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c ^oK	(4) T_c/T_c^o	(5) T_e ^oK	(6) T_e/T_e^o	(7) gm cm^{-3}	(8) $\overline{M}$
0.00	0.00	2957	1.000	2037	1.000	1.28	21.367
3.70	0.25	2913	0.985	1823	0.895	1.24	20.384
7.13	0.50	2783	0.941	1648	0.809	1.20	19.491
13.31	1.00	2479	0.838	1385	0.680	1.13	17.995
18.72	1.50	2193	0.742	1177	0.578	1.08	16.838
23.49	2.00	1948	0.659	1008	0.495	1.04	15.923

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}^o	(14) C_F	(15) h mi.	(16) h/h^o
0.00	5660	7870	244.4	1.000	1.39	460	1.000
3.70	5703	7863	244.2	0.999	1.38	460	1.000
7.13	5587	7774	241.4	0.988	1.39	441	0.959
13.31	5418	7508	233.2	0.954	1.39	405	0.880
18.72	5206	7228	224.5	0.919	1.39	358	0.778
23.49	5018	6958	216.1	0.884	1.39	314	0.683

TABLE XVI

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR RFNA-NH_3(l)-N_2H_4 SYSTEM ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1) WT%	(2) MOLES	(3) T_c °K	(4) T_c/T_c°	(5) T_e °K	(6) T_e/T_e°	(7) $\bar{\rho}$ gm cm^{-3}	(8) $\bar{M}$
0.00	0.00	2957	1.000	1703	1.000	1.28	21.006
3.70	0.25	2913	0.985	1669	0.988	1.24	20.216
7.13	0.50	2763	0.941	1578	0.927	1.20	19.414
13.31	1.00	2479	0.838	1363	0.800	1.13	17.877
18.72	1.50	2193	0.742	1173	0.689	1.08	16.840
23.49	2.00	1948	0.659	1008	0.592	1.04	15.923

(9) WT%	(10) c* ft sec^{-1}	(11) c ft sec^{-1}	(12) I_{sp} sec	(13) I_{sp}/I_{sp}°	(14) C_F	(15) h mi.	(16) h/h°
0.00	5660	7667	238.1	1.000	1.35	437	1.000
3.70	5703	7731	240.1	1.008	1.36	441	1.009
7.13	5587	7690	238.8	1.003	1.38	432	0.989
13.31	5418	7487	232.5	0.976	1.38	402	0.920
18.72	5206	7209	223.9	0.940	1.38	354	0.810
23.49	5018	6958	216.1	0.908	1.39	314	0.719

TABLE XVII

VARIATION OF $E_{(I_{sp})}$ WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR EQUILIBRIUM FLOW CONDITIONS

Propellant systems:

A. N_2O_4-H_2(l)-N_2H_4

B. H_2O_2-H_2(l)-N_2H_4

C. RFNA-H_2(l)-N_2H_4

Wt.% H_2(l)	A	B	C	Average of A,B,C
0.00	0.000	0.000	0.000	0.000
3.00	0.108	0.110	0.124	0.114
6.00	0.236	0.240	0.256	0.244
8.00	0.320	0.314	0.329	0.321
10.00	0.385	0.374	0.388	0.382
12.00	0.440	0.428	0.436	0.435
15.00	0.506	0.496	0.504	0.502
20.00	-	0.580	0.587	0.583
Average Error	0.004	0.006	0.006	
Max. Error	0.008	0.008	0.010	

Errors are with respect to average value obtained by averaging $E_{(I_{sp})}$ of systems A, B, and C.

TABLE XVIII

VARIATION OF E(I_{sp}) WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR CONSTANT COMPOSITION FLOW CONDITIONS

Propellant Systems:

A. N_2O_4-H_2(l)-N_2H_4

B. H_2O_2-H_2(l)-N_2H_4

C. RFNA-H_2(l)-N_2H_4

D. O_2(l)-H_2(l)-$N_2H_4$$^{(a)}$

Wt.% H_2(l)	A	B	C	Average of A,B&C	D
0.00	0.000	0.000	0.000	0.000	0.000
3.00	0.114	0.134	0.144	0.131	0.124
6.00	0.280	0.266	0.282	0.276	0.250
8.00	0.368	0.343	0.358	0.356	0.323
10.00	0.436	0.400	0.416	0.417	0.392
12.00	0.490	0.452	0.464	0.469	0.452
15.00	0.556	0.522	0.530	0.536	0.528
20.00	-	0.606	0.614	0.610	0.630
Average Error	0.015	0.011	0.005		0.016
Max. Error	0.021	0.017	0.013		0.028

Errors are with respect to average value obtained by averaging E(I_{sp}) of systems A, B and C.

(a) Data was computed from values listed in Ref. 3.

TABLE XIX

VARIATION OF $E_{(h)}$ WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR EQUILIBRIUM FLOW CONDITIONS

Propellant Systems:

A. N_2O_4-$H_2(l)$-N_2H_4

B. H_2O_2-$H_2(l)$-N_2H_4

C. RFNA-$H_2(l)$-N_2H_4

Wt.% $H_2(l)$	A	B	C	Average of A,B&C
0.00	0.000	0.000	0.000	0.000
3.00	0.040	0.022	0.052	0.038
6.00	0.080	0.064	0.074	0.073
8.00	0.094	0.088	0.080	0.087
10.00	0.100	0.094	0.089	0.094
12.00	0.105	0.095	0.096	0.099
15.00	0.108	0.096	0.100	0.101
20.00	-	0.080	0.068	0.073
Average Error	0.006	0.006	0.006	
Max. Error	0.007	0.016	0.014	

Errors are with respect to average value obtained by averaging $E_{(h)}$ of systems A, B and C.

TABLE XX

VARIATION OF $E_{(h)}$ WITH WEIGHT PER CENT OF LIQUID HYDROGEN FOR CONSTANT COMPOSITION FLOW CONDITIONS

Propellant Systems:

A. N_2O_4-$H_2(l)$-N_2H_4

B. H_2O_2-$H_2(l)$-N_2H_4

C. RFNA-$H_2(l)$-N_2H_4

Wt.% $H_2(l)$	A	B	C	Average of A, B & C
0.00	0.000	0.000	0.000	0.000
3.00	0.113	0.050	0.086	0.083
6.00	0.164	0.130	0.116	0.137
8.00	0.184	0.149	0.128	0.154
10.00	0.188	0.152	0.136	0.159
12.00	0.190	0.148	0.143	0.160
15.00	0.180	0.144	0.140	0.155
20.00	-	0.124	0.106	0.115
Average Error	0.027	0.009	0.017	
Max. Error	0.030	0.013	0.026	

Errors are with respect to average value obtained by averaging $E_{(h)}$ for systems A, B and C.

TABLE XXI

VARIATION OF $E_{(I_{sp})}$ WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR EQUILIBRIUM FLOW CONDITIONS

Propellant Systems:

D. N_2O_4-$NH_3(l)$-N_2H_4

E. H_2O_2-$NH_3(l)$-N_2H_4

F. RFNA-$NH_3(l)$-N_2H_4

Wt.% $NH_3(l)$	D	E	F	Average of D, E & F
0.00	0.000	0.000	0.000	0.000
3.00	0.012	0.010	0.010	0.011
6.00	0.032	0.028	0.034	0.031
8.00	0.044	0.044	0.056	0.048
10.00	0.060	0.064	0.078	0.067
12.00	0.078	0.088	0.100	0.089
15.00	0.106	0.120	0.136	0.121
20.00	-	0.172	0.190	0.181
Average Error	0.007	0.003	0.008	
Max. Error	0.015	0.009	0.015	

Errors are with respect to average value obtained by averaging $E_{(I_{sp})}$ for systems D, E and F.

TABLE XXII

VARIATION OF $E_{(I_{sp})}$ WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR CONSTANT COMPOSITION FLOW CONDITIONS

Propellant Systems:

D. N_2O_4-NH_3(l)-N_2H_4

E. H_2O_2-NH_3(l)-N_2H_4

F. RFNA-NH_3(l)-N_2H_4

Wt.% NH_3(l)	D	E	F	Average of D, E, & F
0.00	0.000	0.000	0.000	0.000
3.00	0.020	0.020	0.018	0.019
6.00	0.044	0.044	0.050	0.046
8.00	0.063	0.064	0.076	0.068
10.00	0.084	0.086	0.100	0.090
12.00	0.107	0.110	0.123	0.113
15.00	0.141	0.144	0.156	0.147
20.00	-	0.196	0.210	0.203
Average Error	0.004	0.003	0.007	
Max. Error	0.006	0.007	0.010	

Errors are with respect to average value obtained by averaging $E_{(I_{sp})}$ for systems D, E, and F.

TABLE XXIII

VARIATION OF $E_{(h)}$ WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR EQUILIBRIUM FLOW CONDITIONS

Propellant Systems:

D. N_2O_4-$NH_3(l)$-N_2H_4

E. H_2O_2-$NH_3(l)$-N_2H_4

F. RFNA-$NH_3(l)$-N_2H_4

Wt.% $NH_3(l)$	D	E	F	Average of D, E & F
0.00	0.000	0.000	0.000	0.000
3.00	0.012	0.000	0.010	0.007
6.00	0.020	0.000	0.016	0.012
8.00	0.020	0.003	0.023	0.015
10.00	0.021	0.008	0.032	0.020
12.00	0.024	0.016	0.040	0.027
15.00	0.028	0.023	0.042	0.031
20.00	-	0.028	0.032	0.030
Average Error	0.004	0.009	0.007	
Max. Error	0.008	0.012	0.015	

Errors are with respect to average value obtained by averaging $E_{(h)}$ for systems D, E, and F.

TABLE XXIV

VARIATION OF $E_{(h)}$ WITH WEIGHT PER CENT OF LIQUID AMMONIA FOR CONSTANT COMPOSITION FLOW CONDITIONS

Propellant Systems:

D. N_2O_4-$NH_3(l)$-N_2H_4

E. H_2O_2-$NH_3(l)$-N_2H_4

F. RFNA-$NH_3(l)$-N_2H_4

Wt.% $NH_3(l)$	D	E	F	Average of D, E and F
0.00	0.000	0.000	0.000	0.000
5.00	0.028	0.016	0.018	0.021
6.00	0.060	0.042	0.042	0.048
8.00	0.076	0.058	0.060	0.065
10.00	0.088	0.070	0.072	0.077
12.00	0.103	0.080	0.080	0.088
15.00	0.106	0.080	0.084	0.090
20.00	-	0.070	0.064	0.067
Average Error	0.012	0.007	0.005	
Max. Error	0.016	0.010	0.008	

Errors are with respect to average value obtained by averaging $E_{(h)}$ for systems D, E and F.

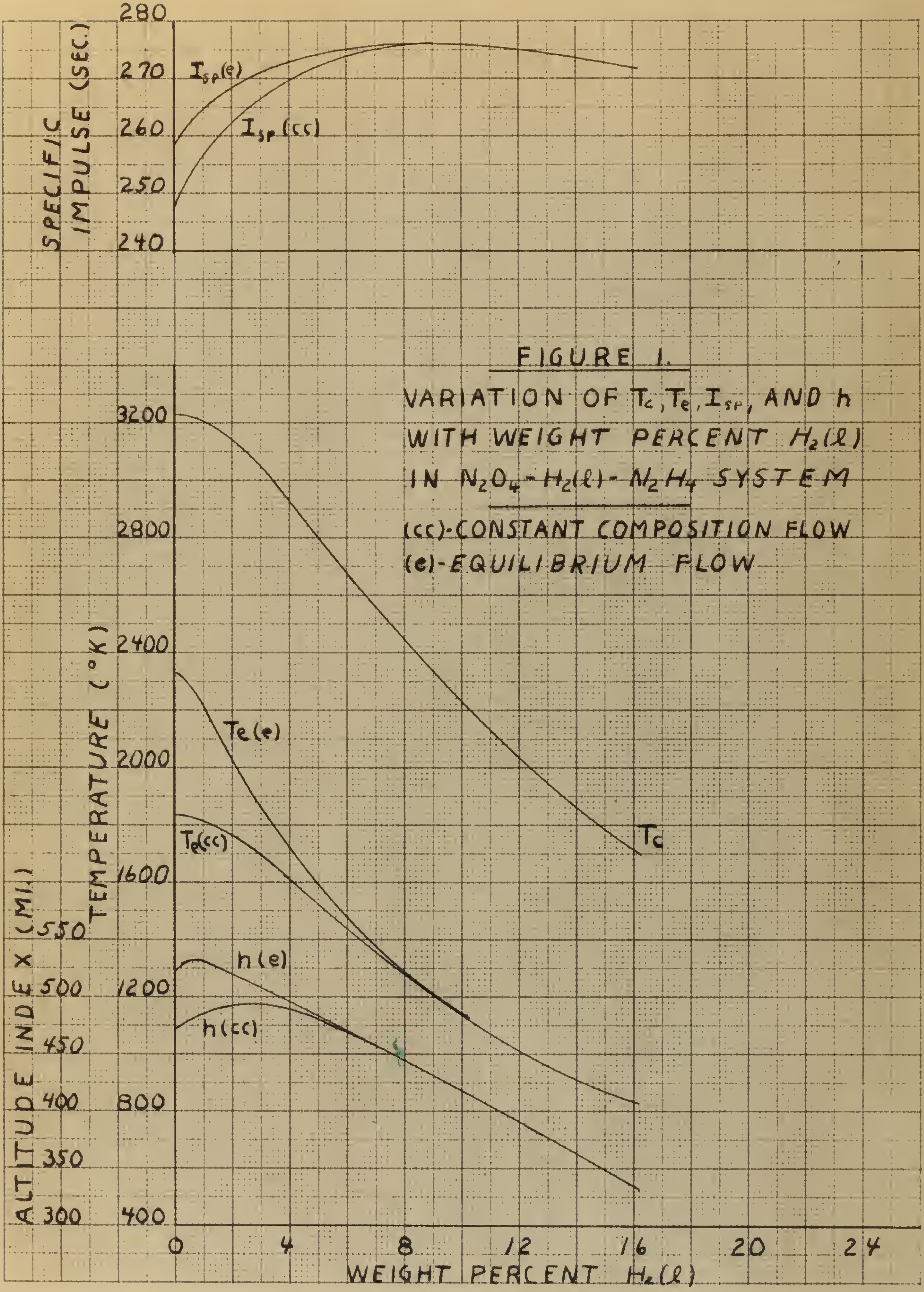


FIGURE 1.

VARIATION OF T_c, T_e, I_{sp}, AND h WITH WEIGHT PERCENT $H_2(\ell)$ IN N_2O_4-$H_2(\ell)$-N_2H_4 SYSTEM

(cc)-CONSTANT COMPOSITION FLOW
(e)-EQUILIBRIUM FLOW

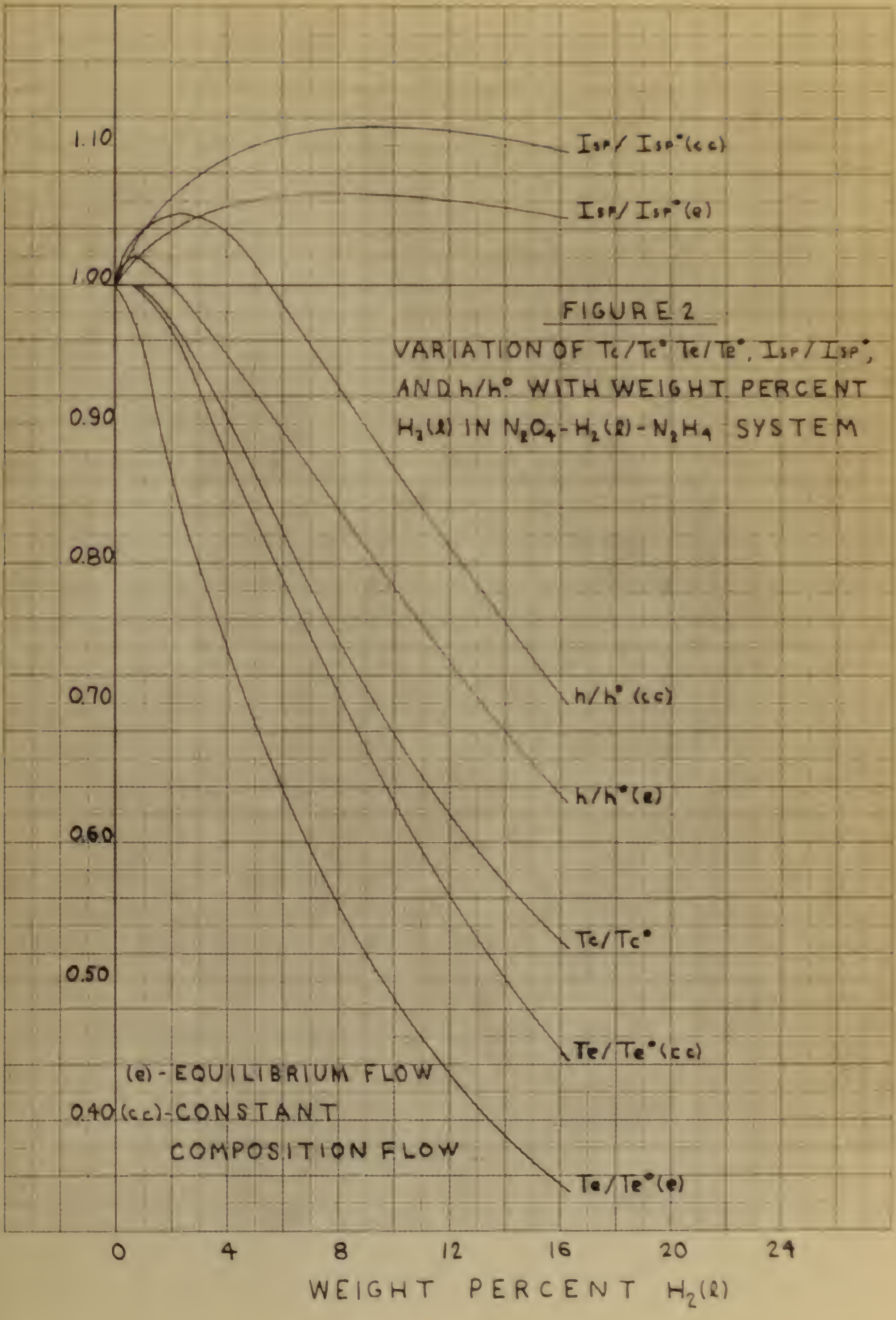


FIGURE 2

VARIATION OF T_c/T_c° T_e/T_e°, I_{sp}/I_{sp}°, AND h/h° WITH WEIGHT PERCENT $H_2(l)$ IN N_2O_4-$H_2(l)$-N_2H_4 SYSTEM

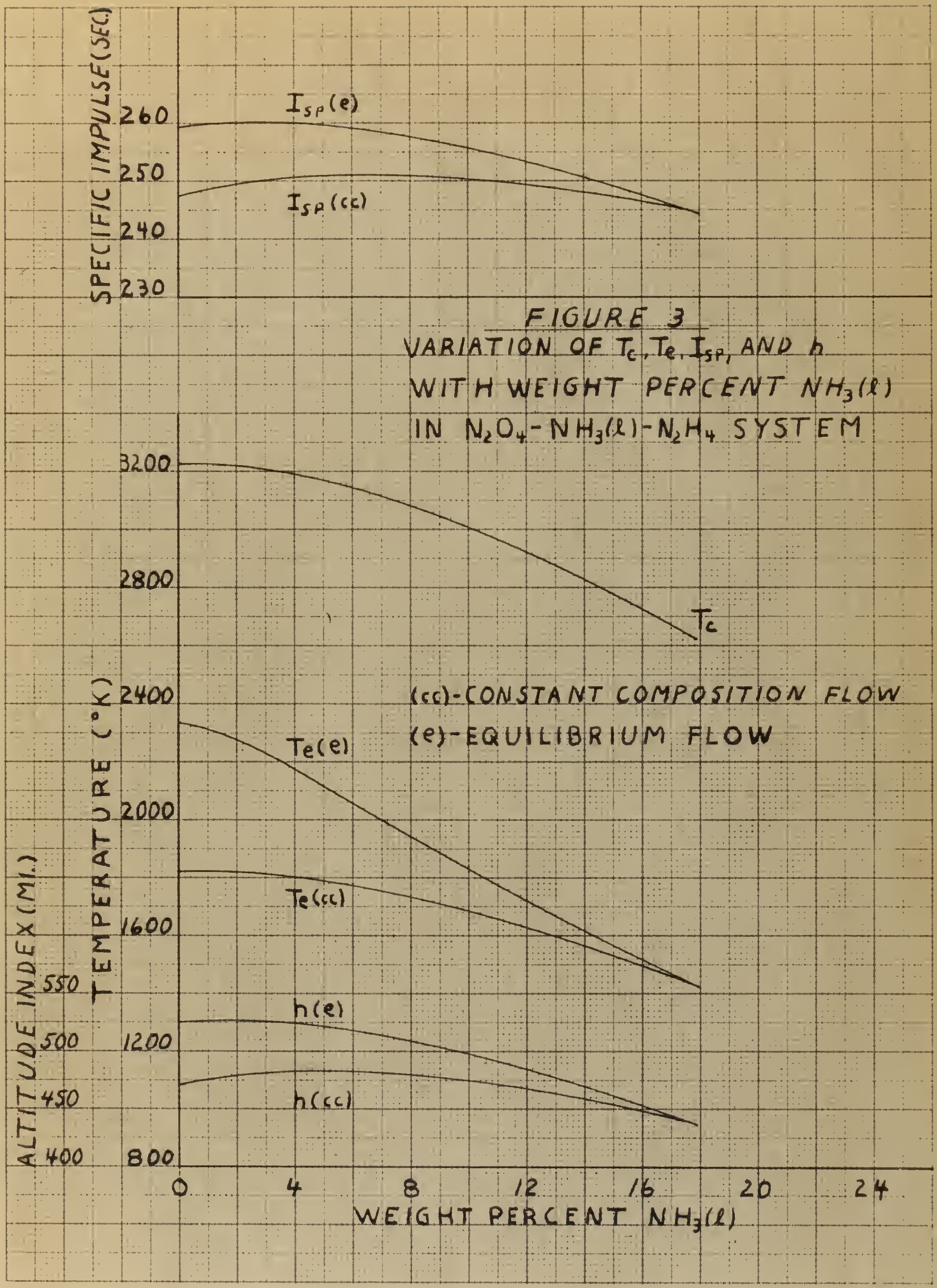


FIGURE 3

VARIATION OF T_c, T_e, I_{sp}, AND h WITH WEIGHT PERCENT $NH_3(\ell)$ IN N_2O_4-$NH_3(\ell)$-N_2H_4 SYSTEM

(cc)-CONSTANT COMPOSITION FLOW

(e)-EQUILIBRIUM FLOW

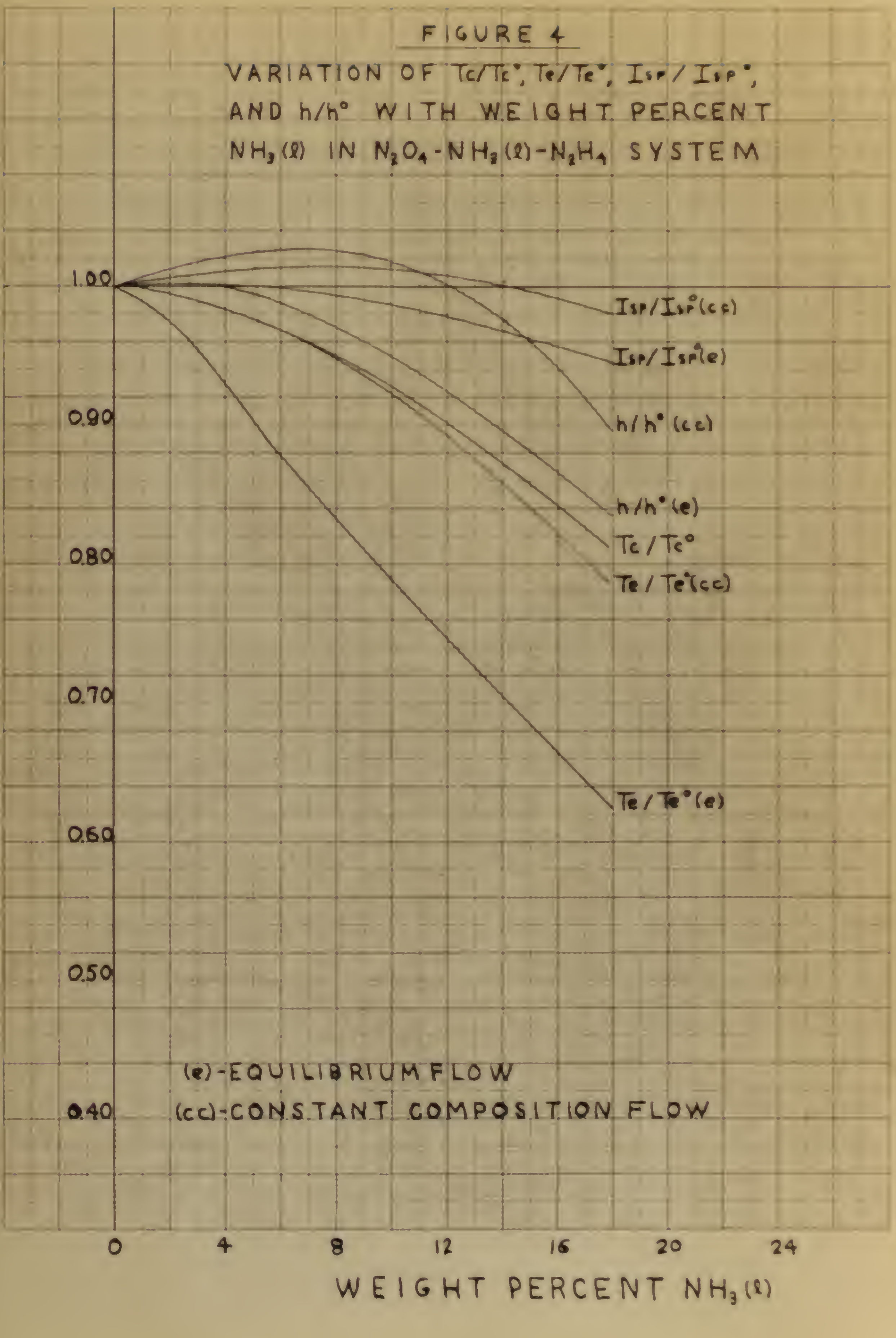


FIGURE 4

VARIATION OF T_c/T_c°, T_e/T_e°, I_{sp}/I_{sp}°, AND h/h° WITH WEIGHT PERCENT $NH_3(\ell)$ IN N_2O_4-$NH_3(\ell)$-N_2H_4 SYSTEM

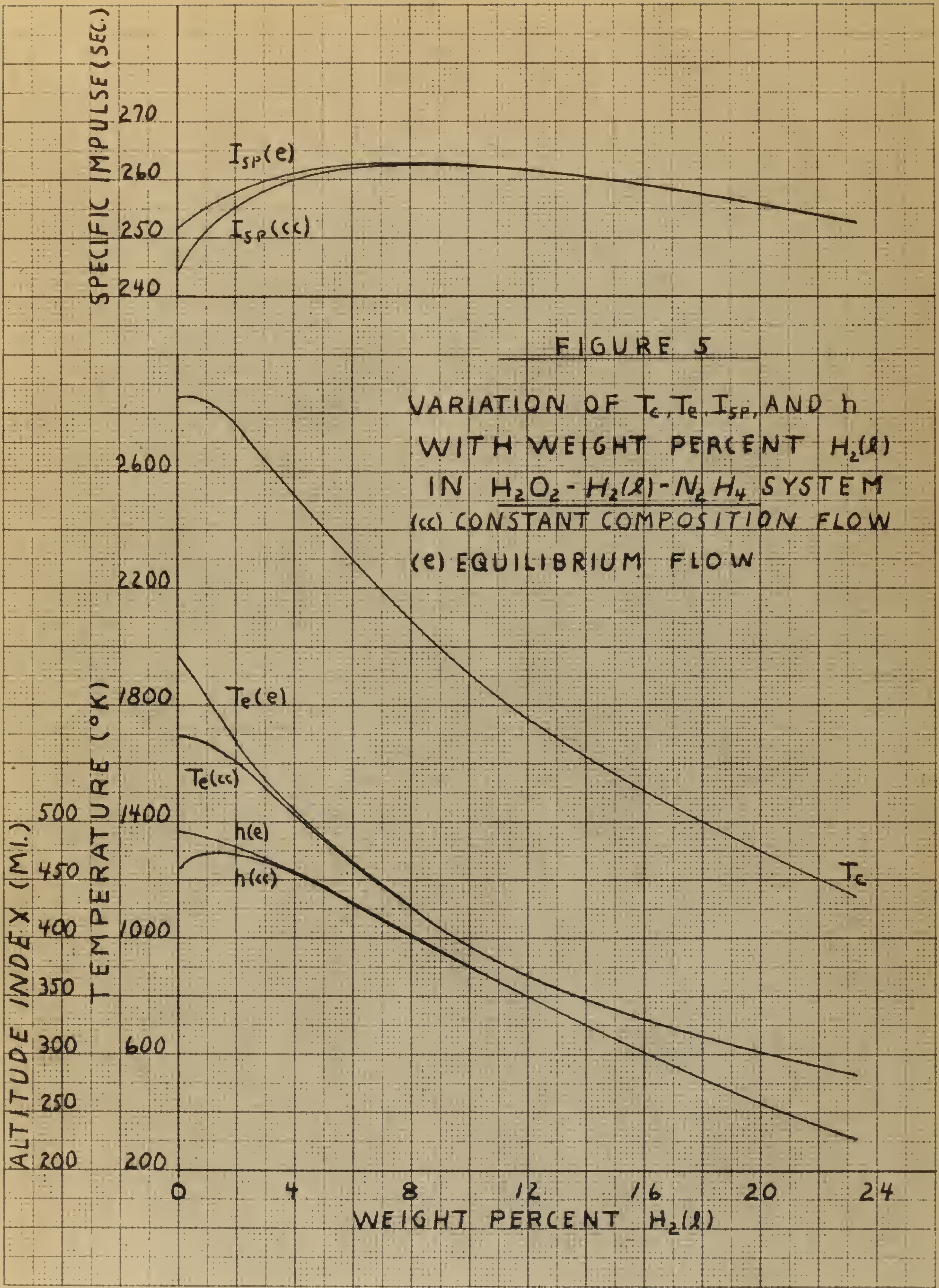


FIGURE 5

VARIATION OF T_c, T_e, I_{sp}, AND h WITH WEIGHT PERCENT $H_2(\ell)$ IN H_2O_2 - $H_2(\ell)$ - N_2H_4 SYSTEM

(cc) CONSTANT COMPOSITION FLOW

(e) EQUILIBRIUM FLOW

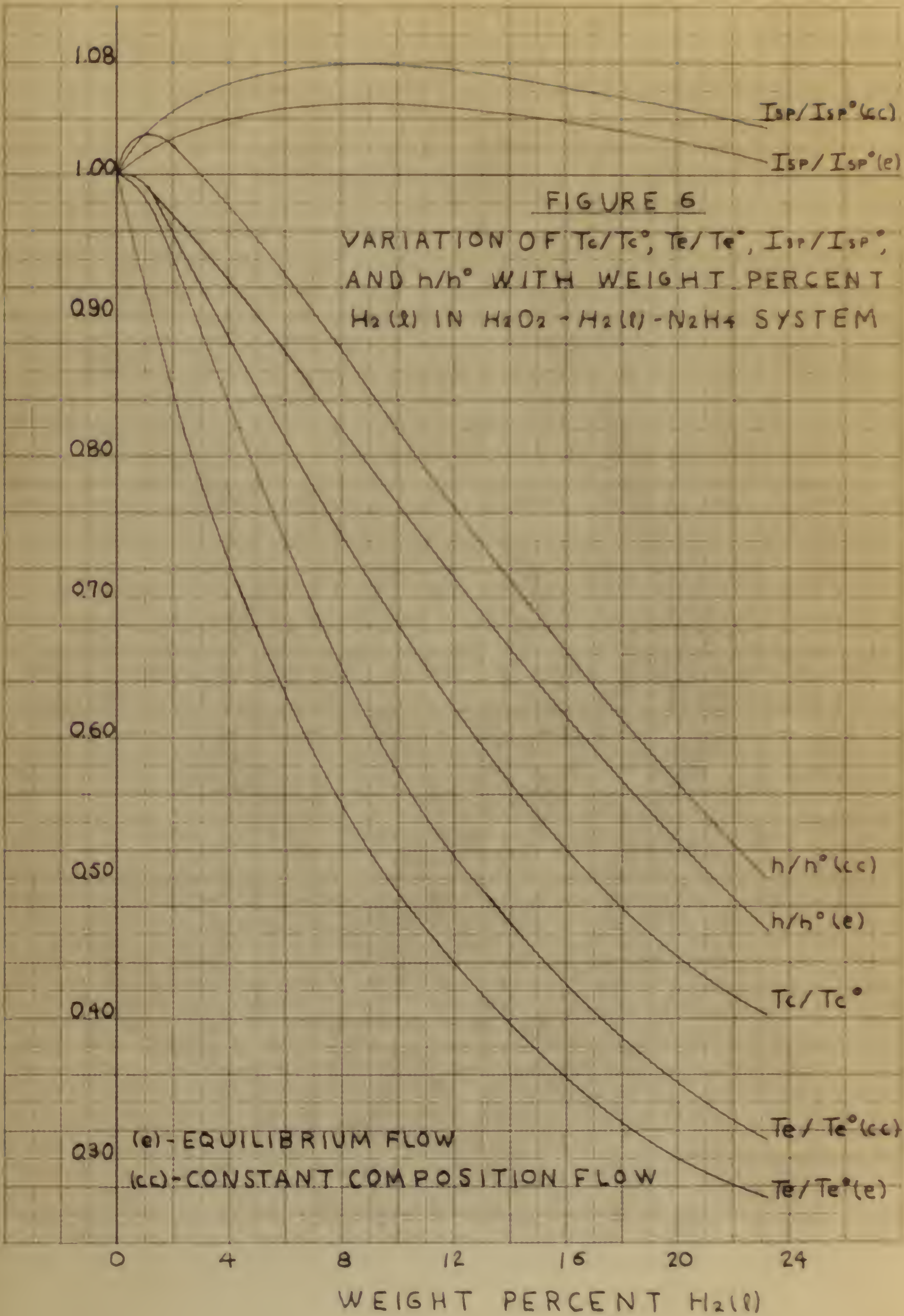


FIGURE 6

VARIATION OF Tc/Tc°, Te/Te°, Isp/Isp°, AND h/h° WITH WEIGHT PERCENT $H_2(l)$ IN $H_2O_2-H_2(l)-N_2H_4$ SYSTEM

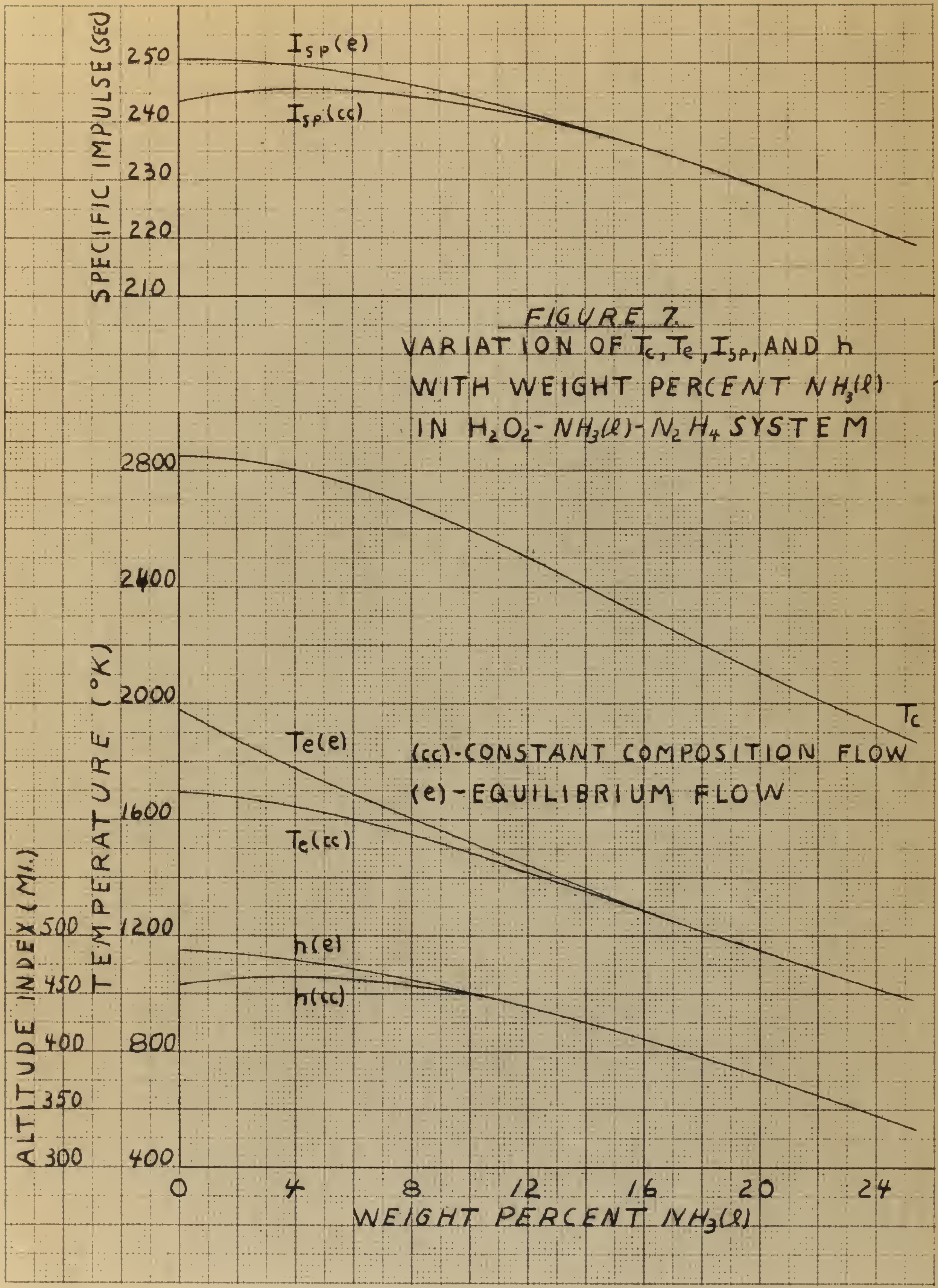


FIGURE 7.
VARIATION OF T_c, T_e, I_{sp}, AND h WITH WEIGHT PERCENT $NH_3(l)$ IN H_2O_2-$NH_3(l)$-N_2H_4 SYSTEM

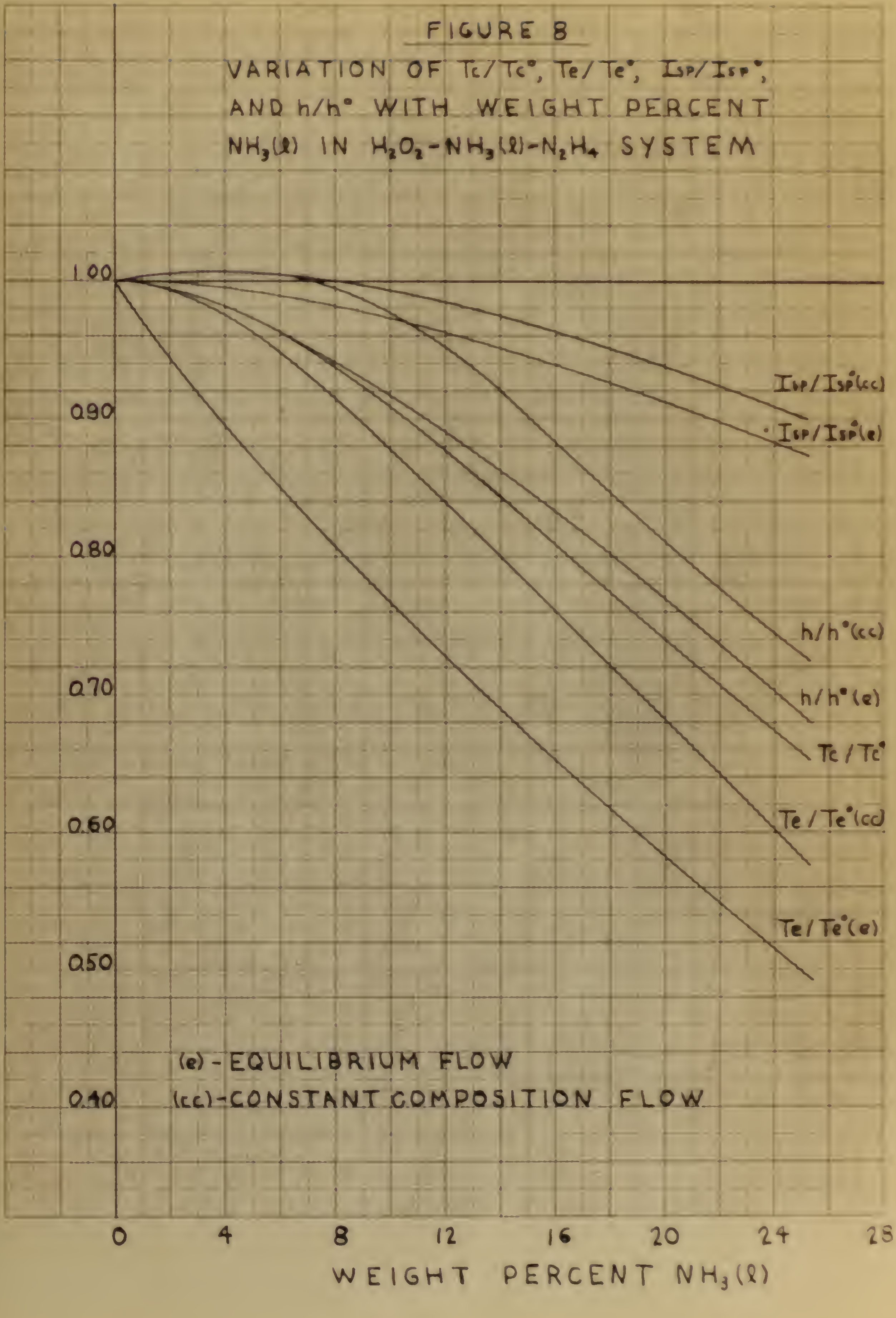


FIGURE 8

VARIATION OF $T_c/T_c°$, $T_e/T_e°$, $I_{sp}/I_{sp}°$, AND $h/h°$ WITH WEIGHT PERCENT $NH_3(l)$ IN $H_2O_2-NH_3(l)-N_2H_4$ SYSTEM

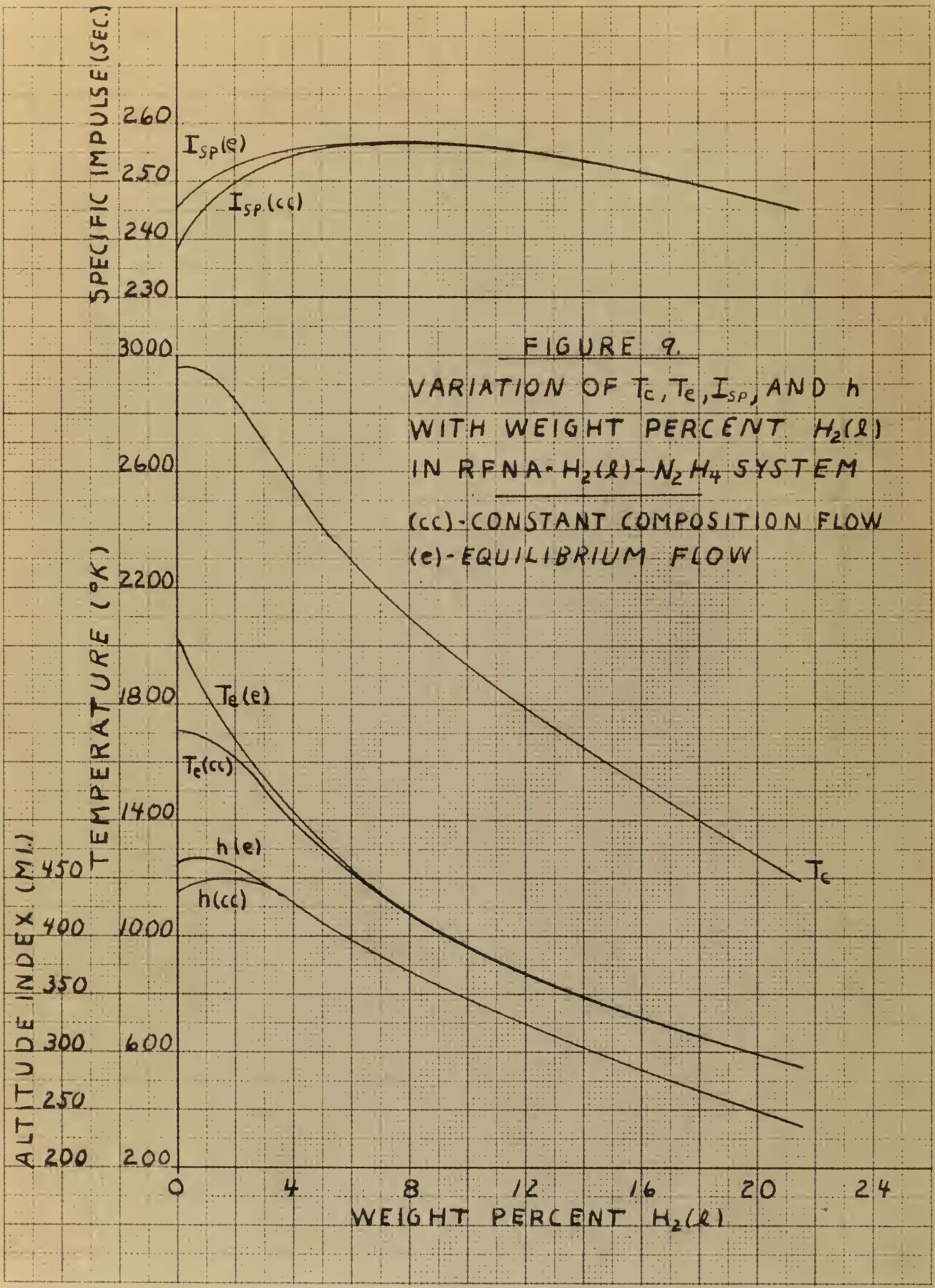


FIGURE 9.

VARIATION OF T_c, T_e, I_{sp}, AND h WITH WEIGHT PERCENT $H_2(\ell)$ IN RFNA-$H_2(\ell)$-N_2H_4 SYSTEM

(cc)-CONSTANT COMPOSITION FLOW

(e)-EQUILIBRIUM FLOW

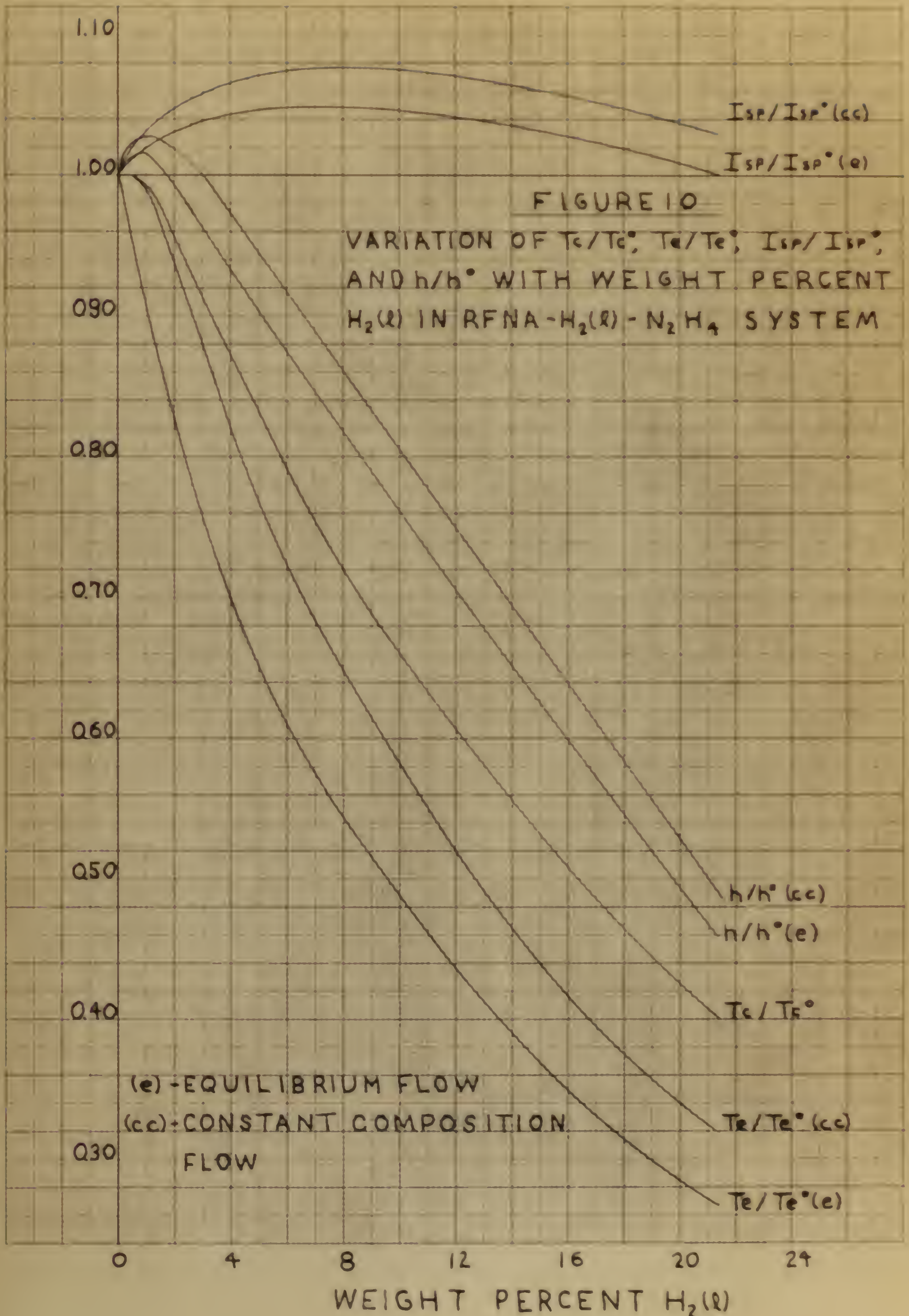


FIGURE 10

VARIATION OF T_c/T_c°, T_e/T_e°, I_{sp}/I_{sp}°, AND h/h° WITH WEIGHT PERCENT $H_2(\ell)$ IN RFNA-$H_2(\ell)$-N_2H_4 SYSTEM

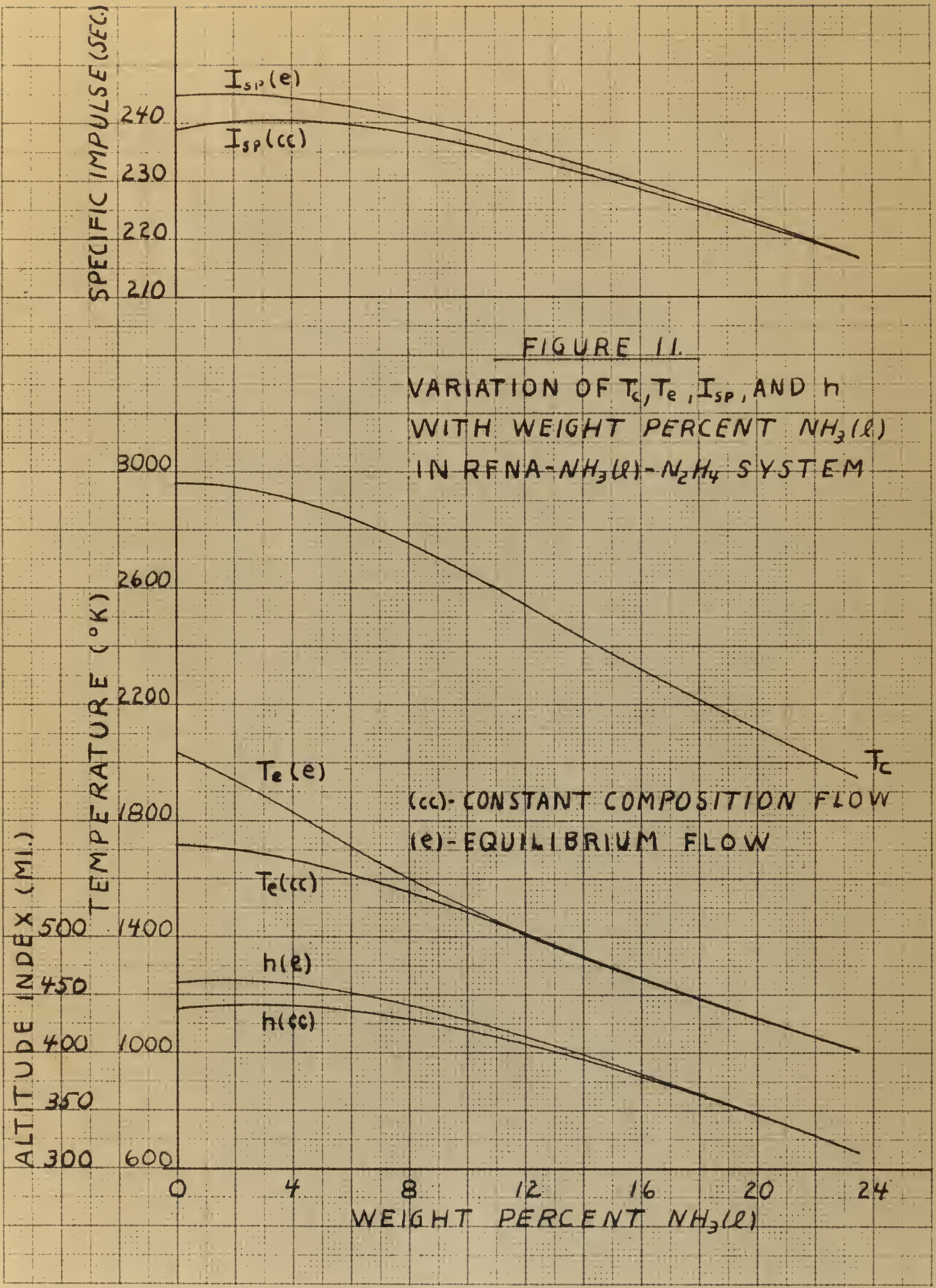


FIGURE 11

VARIATION OF T_c, T_e, I_{sp}, AND h WITH WEIGHT PERCENT $NH_3(\ell)$ IN RFNA-$NH_3(\ell)$-N_2H_4 SYSTEM

(cc)- CONSTANT COMPOSITION FLOW

(e)- EQUILIBRIUM FLOW

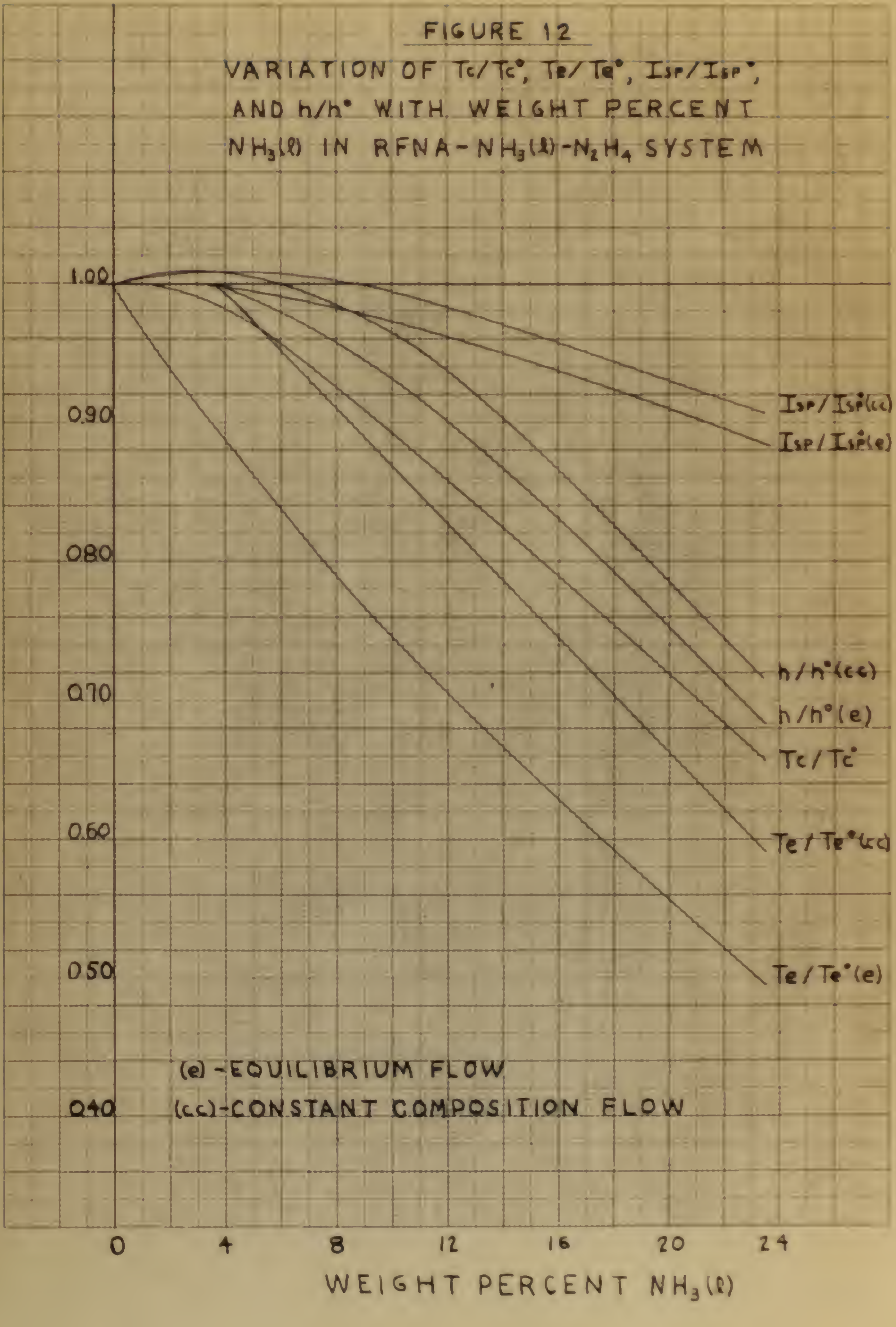


FIGURE 12

VARIATION OF Tc/Tc°, Te/Te°, Isp/Isp°, AND h/h° WITH WEIGHT PERCENT $NH_3(l)$ IN RFNA-$NH_3(l)$-N_2H_4 SYSTEM

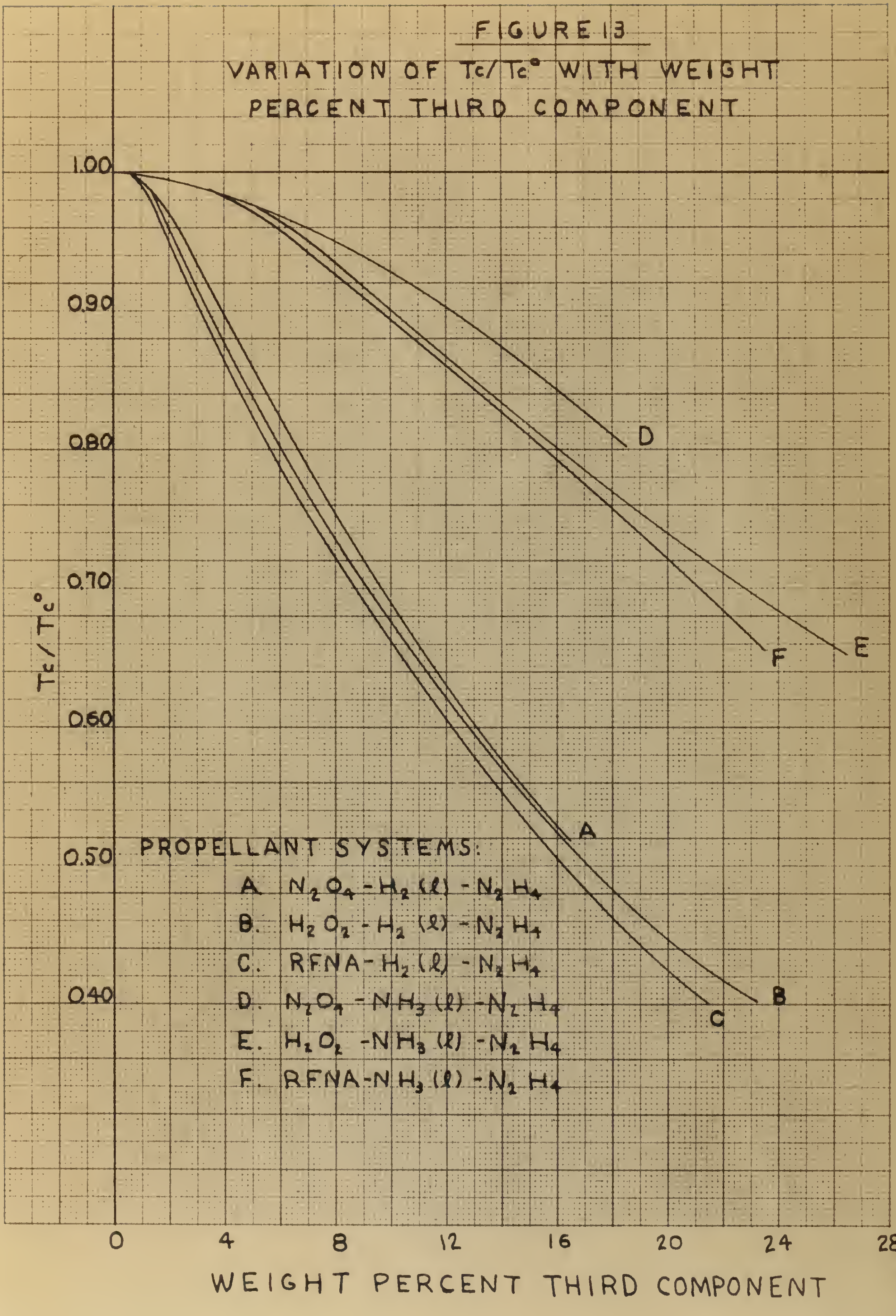


FIGURE 13

VARIATION OF T_c/T_c° WITH WEIGHT PERCENT THIRD COMPONENT

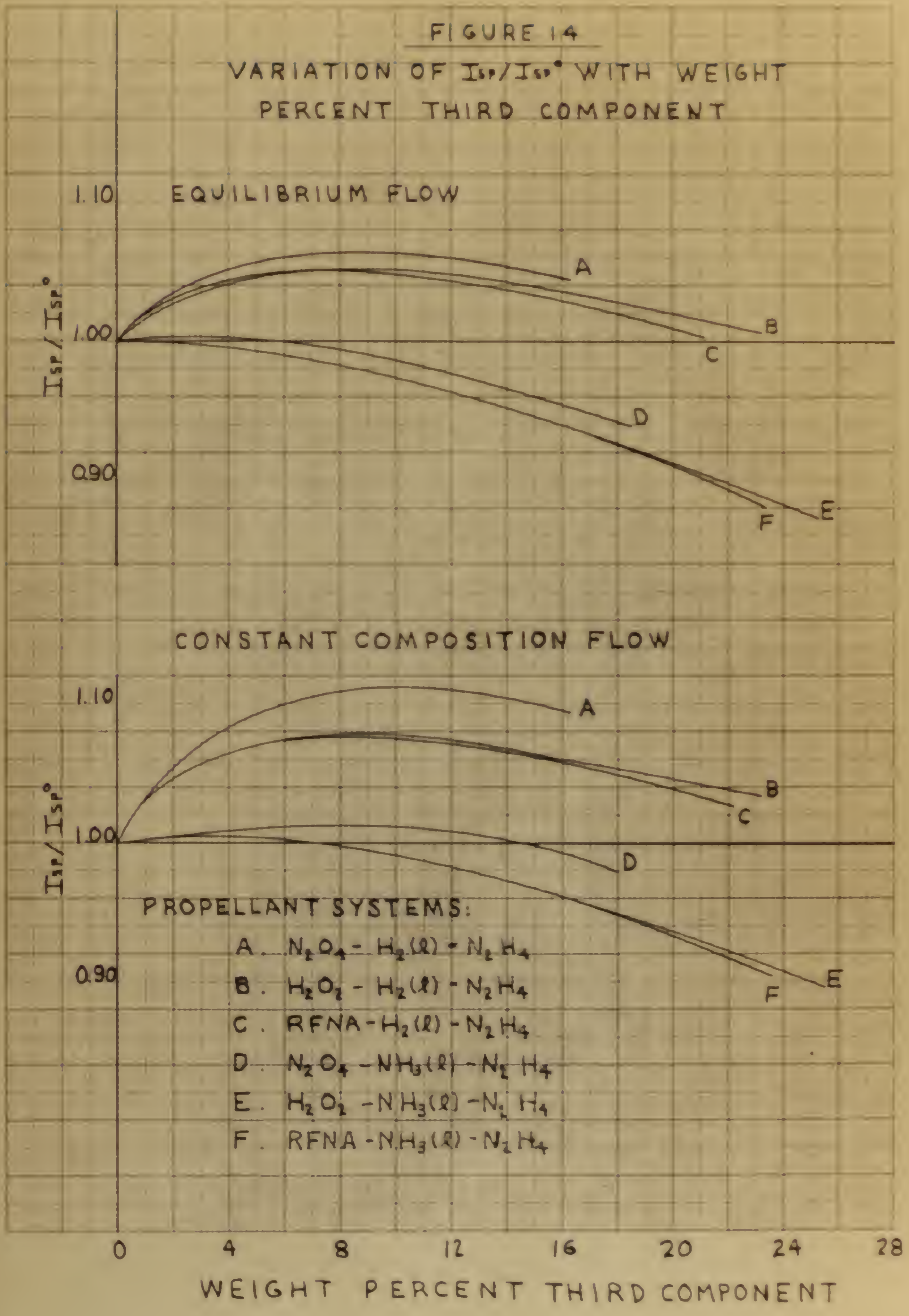


FIGURE 14

VARIATION OF I_{sp}/I_{sp}° WITH WEIGHT PERCENT THIRD COMPONENT

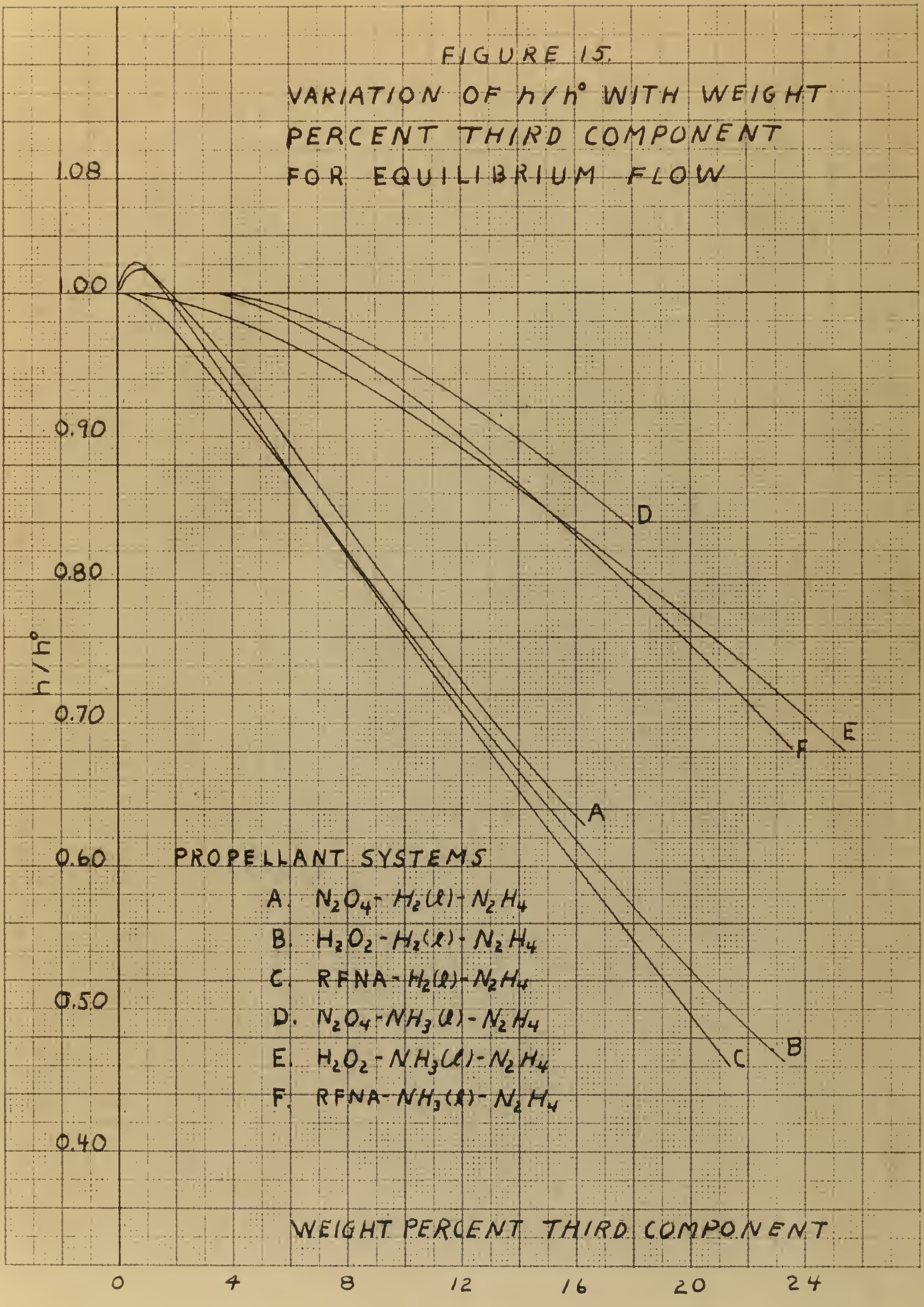


FIGURE 15.
VARIATION OF h/h° WITH WEIGHT PERCENT THIRD COMPONENT FOR EQUILIBRIUM FLOW

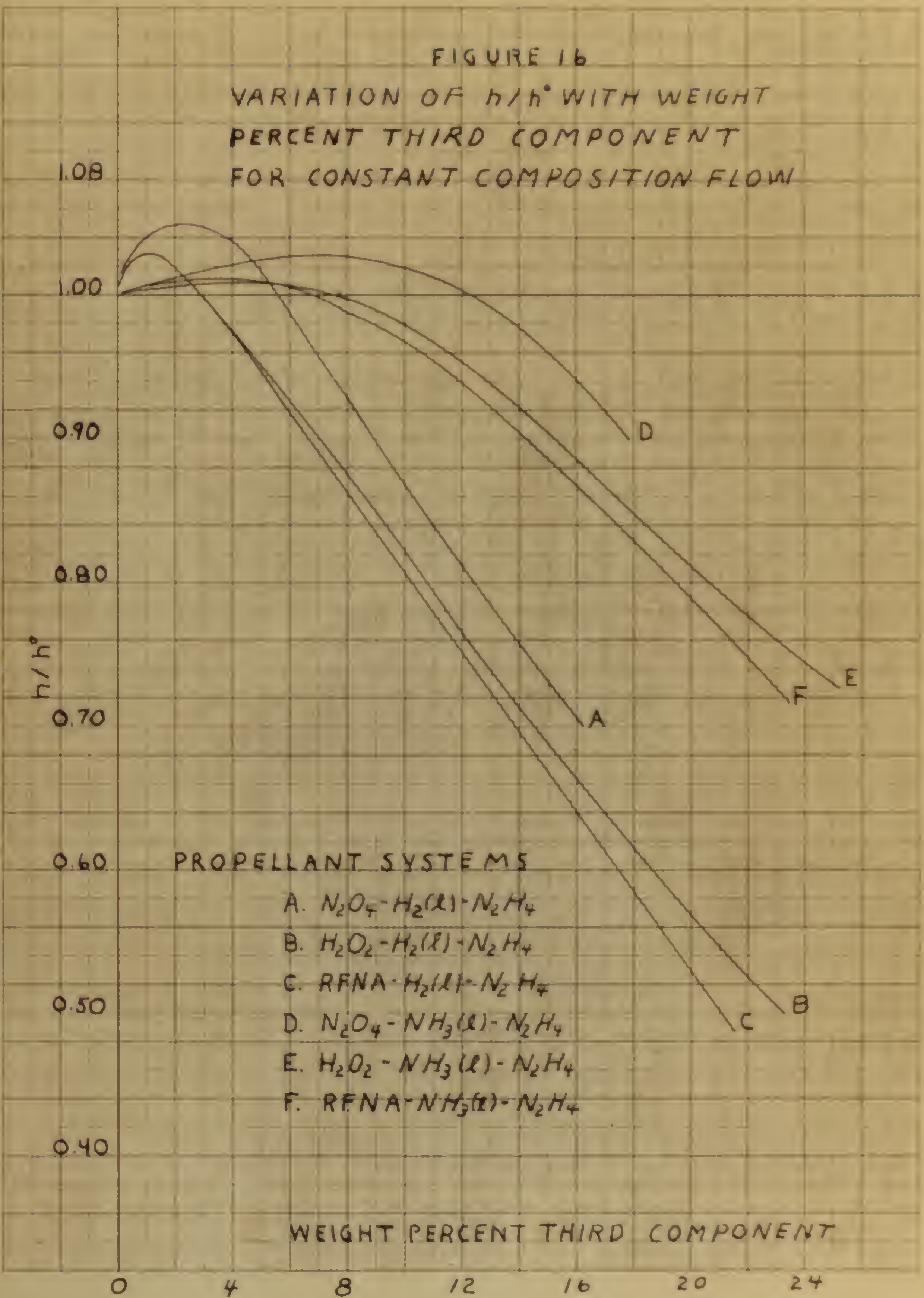
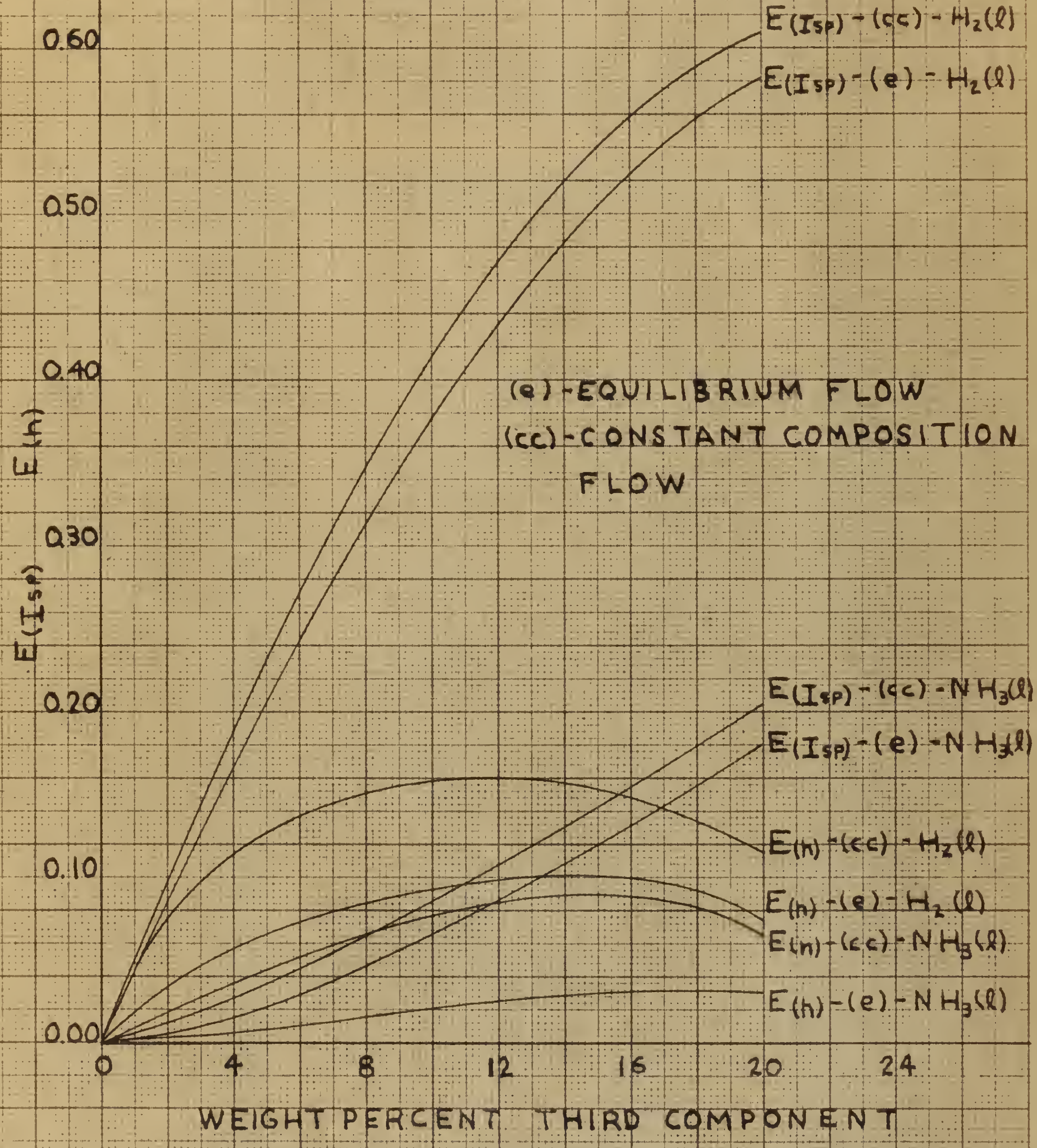


FIGURE 16

VARIATION OF h/h° WITH WEIGHT PERCENT THIRD COMPONENT FOR CONSTANT COMPOSITION FLOW

FIGURE 17

VARIATION OF $E(I_{sp})$ AND $E(h)$ WITH WEIGHT PERCENT THIRD COMPONENT



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